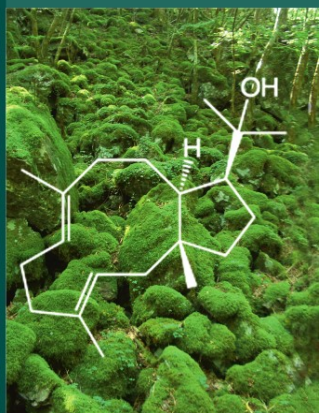
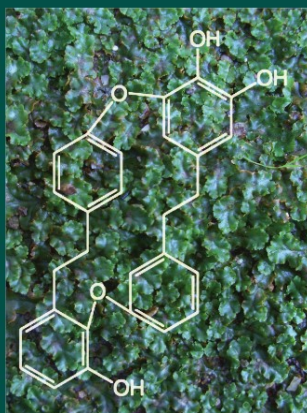
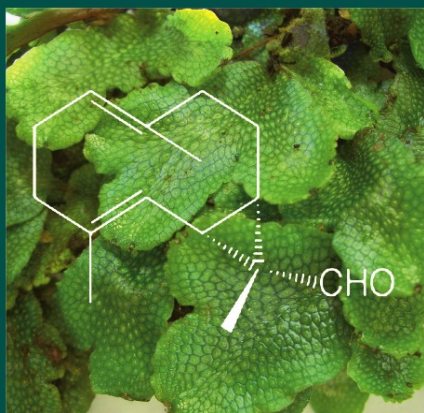


Y. Asakawa
A. Ludwiczuk
F. Nagashima

Chemical Constituents of Bryophytes

Bio- and Chemical Diversity,
Biological Activity, and Chemosystematics



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of Organic Natural Products

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Dedicated to the memory of Guy Ourisson and Meinhart Zenk

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1 Introduction

The first review dealing with chemical constituents of the Marchantiophyta (liverworts) appeared in this series as Volume 42 in 1982 (39). A second one was issued as Volume 65 in 1995 (40). These included the chemical constituents, their biological activity and chemosystematics not only of the Marchantiophyta, but also of the Bryophyta (mosses) and the Anthocerotophyta (hornworts). Two short review articles of the chemical constituents of bryophytes and the distribution of mono-, sesqui- and diterpenoids in bryophytes and synthesis of a few secondary metabolites have been reported in 1994 by Zinsmeister and associates (987) and by Connolly (160).

The further development and application of NMR spectroscopy at high fields such as 500, 600, and 700 MHz, two-dimensional (2D) NMR techniques, HPLC-NMR, electron ionization time-of-flight (EI-TOF) and electrospray ionization (ESI) triple-quadrupole mass spectrometry, and liquid chromatography/tandem mass spectrometry, among other methods, have resulted in a dramatic increase of papers concerned with the structure elucidation of chemical constituents isolated from the bryophytes. In the present review, the biological and chemical diversity of the Marchantiophyta, the isolation, structural characterization and total synthesis of naturally occurring terpenoids, aromatic compounds, and lipids of the bryophytes encountered after 1995, as well as their biological activity and the chemosystematics of the bryophytes, and the chemical relationships between algae, bryophytes, and pteridophytes are summarized. The organization of the material presented follows that adopted in the previous review.

The bryophytes are found everywhere in the world except in the sea. They grow on trees, rocks, in the soil, in lakes, and in rivers from the tundra of the Northern hemisphere to Antarctica. The bryophytes (Fig. 1.1) are placed taxonomically between the algae (Fig. 1.2) and the pteridophytes (Fig. 1.3) and 25,000 species are now known world-wide. These are divided into three classes, namely, Bryophyta (mosses, 14,000 species), Marchantiophyta (liverworts, 6,000 species), and Anthocerotophyta (hornworts 300 species). They are considered to be the oldest terrestrial plants, although no strong scientific evidence for this assertion has appeared in literature. This hypothesis is based mainly on the resemblance of



Fig. 1.1 Bryophyte



Fig. 1.2 Alga

the present-day liverworts to the first land plant fossils, for which the spores date back almost 500 million years. A representative liverwort, moss, and hornwort are exemplified in Figs. 1.4–1.6, respectively.

Among the bryophytes, almost all liverworts possess appealing cellular oil bodies (Fig. 1.7) which are characteristic, membrane-bound cell organelles consisting of ethereal terpenoids and aromatic oils suspended in a carbohydrate- or a protein-rich matrix, while the other two phyla do not. These oil bodies are very important markers for the classification of the Marchantiophyta.



Fig. 1.3 Pteridophyte

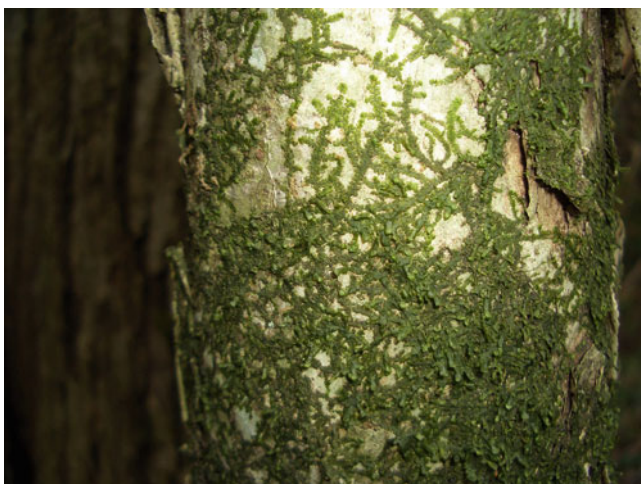


Fig. 1.4 Liverwort

In a modern classification of the bryophytes, the Marchantiophyta are divided into three classes, seven subclasses, and 15 orders (Table 1.1) (168, 169), while the Bryophyta are divided into five superclasses, eight classes and 30 orders (Table 1.2) (258), and the Anthocerotae comprises only five families (Table 1.3) (676).

Among the bryophytes, the chemical constituents of the Marchantiophyta have been studied in the most detail, because of the cellular oil bodies found in liverwort that are absent in mosses and hornworts.



Fig. 1.5 Moss



Fig. 1.6 Hornwort. (Permission for the use of this figure has been obtained from Mr. *Masana Izawa*, Saitama, Japan)

Mues estimated that only 6% of all liverwort species have been investigated chemically (554). *Markham* has indicated that the analogous figure for mosses is probably less than 2% (508).

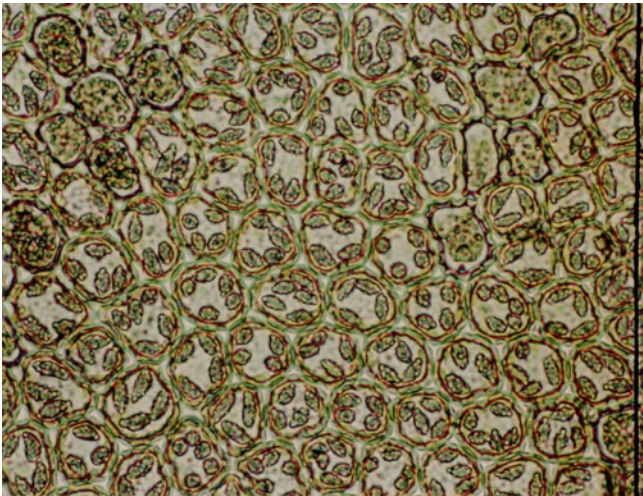


Fig. 1.7 Oil bodies

Table 1.1 Classification of the Marchantiophyta (168, 169)

Class:	Haplomitriopsida
Subclass:	Treubiidae
Order:	Treubiales
Family:	Treubiaceae: <i>Apotreubia</i> , <i>Treubia</i>
Subclass:	Haplomitriidae
Order:	Calobryales
Family:	Haplomitriaceae: <i>Haplomitrium</i> ^a , <i>Gessella</i>
Class:	Marchantiopsida
Subclass:	Blasiidae
Order:	Blasiales
Family:	Blasiaceae: <i>Blasia</i> , <i>Cavicularia</i>
Subclass:	Marchantiidae
Order:	Sphaerocarpales
Family:	Shaerocarpaceae: <i>Geothallus</i> , <i>Sphaerocarpos</i>
	Riellaceae: <i>Riella</i>
Order:	Neohodgsoniales
Family:	Neohodgsoniaceae: <i>Neohodgsonia</i>
Order:	Lunulariales
Family:	Lunulariaceae: <i>Lunularia</i>
Order:	Marchantiales
Family:	Aytoniaceae: <i>Asterella</i> , <i>Cryptomitrium</i> , <i>Mannia</i> , <i>Plagiochasma</i> , <i>Reboulia</i>
	Cleveaceae: <i>Athalamia</i> , <i>Sauteria</i> , <i>Peltolepsis</i>
	Conocephalaceae: <i>Conocephalum</i>
	Corsiniaceae: <i>Corsinia</i>
	Cyathodiaceae: <i>Cyathodium</i>

(continued)

Table 1.1 (continued)

	Dumortieraceae: <u>Dumortiera</u>
	Exormothecaceae: <u>Aitchisoniella</u> , <u>Exormotheca</u> , <u>Stephensoniella</u>
	Marchantiaceae: <u>Bucegia</u> , <u>Marchantia</u> , <u>Preissia</u>
	Monocarpaceae: <u>Monocarpus</u>
	Monocleaceae: <u>Monoclea</u>
	Monosoleniaceae: <u>Monosolenium</u>
	Oxymitraceae: <u>Oxymitra</u>
	Ricciaceae: <u>Riccia</u> , <u>Ricciocarpus</u>
	Targioniaceae: <u>Targonia</u>
	Wiesnerellaceae: <u>Wiesnerella</u>
Class:	Jungermanniopsida
Subclass:	Pelliidae
Order:	Pelliales
Family:	Pelliaceae: <u>Pellia</u> , <u>Noteroclada</u>
Order:	Fossombroniales
Suborder:	Calyculariineae
Family:	Calyculariaceae: <u>Calycularia</u>
Suborder:	Makinoineae
Family:	Makinoaceae: <u>Makinoa</u>
Suborder:	Fossombroniineae
Family:	Allisoniaceae: <u>Allisonia</u>
	Fossombroniaceae: <u>Fossombronia</u> , <u>Austrofossombronia</u>
	Petalophyllaceae: <u>Petaphyllum</u> , <u>Sewardiella</u>
Order:	Pallaviciniales
Suborder:	Phyllothalliineae
Family:	Phyllothalliaceae: <u>Phyllothallia</u>
Suborder:	Pallaviciniineae
Family:	Hymenophytaceae: <u>Hymenophyton</u>
	Moerckiaceae: <u>Hattorianthus</u> , <u>Moerckia</u>
	Pallaviciniaceae: <u>Greeneothallus</u> , <u>Jensenia</u> , <u>Pallavicinia</u> , <u>Podomotrium</u> , <u>Symphyogyna</u> , <u>Symphyogynopsis</u> , <u>Xenothallus</u>
	Sandeothallaceae: <u>Sandeothallus</u>
Subclass:	Metzgeriidae
Order:	Pleuroziales
Family:	Pleuroziaceae: <u>Pleurozia</u> , <u>Eopleurozia</u>
Order:	Metzgeriales
Family:	Metzgeriaceae: <u>Apometzgeria</u> , <u>Austrometzgeria</u> , <u>Metzgeria</u> , <u>Steereella</u>
	Aneuraceae: <u>Aneura</u> , <u>Cryptothallus</u> , <u>Riccardia</u> , <u>Lobatiriccardia</u> , <u>Verdoornia</u>
	Mizutaniaceae: <u>Mizutania</u>
	Vandiemeniaceae: <u>Vandiemenia</u>
Subclass:	Jungermanniidae
Order:	Porellales
Suborder:	Porellineae
Family:	Porellaceae: <u>Ascidiota</u> , <u>Macvicaria</u> , <u>Porella</u>
	Goebeliellaceae: <u>Goebeliella</u>
	Lepidolaenaceae: <u>Gackstroemia</u> , <u>Lepidogyna</u> , <u>Lepidolaena</u> , <u>Jubulopsis</u>

(continued)

Table 1.1 (continued)

Suborder:	Radulineae
Family:	Radulaceae: <u>Radula</u>
Suborder:	Jubulineae
Family:	Frullaniaceae: <u>Frullania</u> , <u>Amphijubula</u> , <u>Neohattoria</u> , <u>Schusterella</u> , <u>Steerea</u> Jubulaceae: <u>Jubula</u> , <u>Nipponolejeunea</u> Lejeuneaceae: <u>Acanthocoleus</u> , <u>Acantholejeunea</u> , <u>Acrolejeunea</u> , <u>Amblyolejeunea</u> , <u>Amphilejeunea</u> , <u>Anoplolejeunea</u> , <u>Aphanolejeunea</u> , <u>Aphanotropis</u> , <u>Archilejeunea</u> , <u>Aureolejeunea</u> , <u>Austrolejeunea</u> , <u>Blepharolejeunea</u> , <u>Brachiolejeunea</u> , <u>Bromeliophila</u> , <u>Bryopteris</u> , <u>Calatholejeunea</u> , <u>Capillolejeunea</u> , <u>Caudalejeunea</u> , <u>Cephalantholejeunea</u> , <u>Cephalolejeunea</u> , <u>Ceratolejeunea</u> , <u>Cheilolejeunea</u> , <u>Cyrtolejeunea</u> , <u>Chondriolejeunea</u> , <u>Cladolejeunea</u> , <u>Cololejeunea</u> , <u>Colura</u> , <u>Crossotolejeunea</u> , <u>Cryptogynolejeunea</u> , <u>Cyclolejeunea</u> , <u>Cystolejeunea</u> , <u>Dactylolejeunea</u> , <u>Dactylophorella</u> , <u>Dendrolejeunea</u> , <u>Didladolejeunea</u> , <u>Dicranolejeunea</u> , <u>Diplasiolejeunea</u> , <u>Drepanolejeunea</u> , <u>Echinocolea</u> , <u>Echinolejeunea</u> , <u>Evansiolejeunea</u> , <u>Frullanoides</u> , <u>Fulfordianthus</u> , <u>Haplolejeunea</u> , <u>Harpalejeunea</u> , <u>Hattorirolejeunea</u> , <u>Kymatolejeunea</u> , <u>Leirolejeunea</u> , <u>Lejeunea</u> , <u>Lepidolejeunea</u> , <u>Leptolejeunea</u> , <u>Leucolejeunea</u> , <u>Lindigianthus</u> , <u>Lopholejeunea</u> , <u>Luteolejeunea</u> , <u>Macrocolura</u> , <u>Macrolejeunea</u> , <u>Marchesia</u> , <u>Mastigolejeunea</u> , <u>Metalejeunea</u> , <u>Metzgeriopsis</u> , <u>Microlejeunea</u> , <u>Myriocolea</u> , <u>Myriocoleopsis</u> , <u>Neopotamolejeunea</u> , <u>Nephelolejeunea</u> , <u>Neurolejeunea</u> , <u>Odontolejeunea</u> , <u>Omphalanthus</u> , <u>Oryzolejeunea</u> , <u>Otolejeunea</u> , <u>Phaeolejeunea</u> , <u>Physantholejeunea</u> , <u>Pictolejeunea</u> , <u>Pluvianthus</u> , <u>Prionolejeunea</u> , <u>Ptychanthus</u> , <u>Pycnolejeunea</u> , <u>Rectolejeunea</u> , <u>Rhaphidolejeunea</u> , <u>Schiffneriolejeunea</u> , <u>Schusterolejeunea</u> , <u>Siphonolejeunea</u> , <u>Sphaerolejeunea</u> , <u>Spruceanthus</u> , <u>Stenolejeunea</u> , <u>Stictolejeunea</u> , <u>Symbiezidium</u> , <u>Taxilejeunea</u> , <u>Thysananthus</u> , <u>Trachylejeunea</u> , <u>Potamolejeunea</u> , <u>Trocholejeunea</u> , <u>Tuyamaella</u> , <u>Tuzibeanthus</u> , <u>Verdoornianthus</u> , <u>Vitalianthus</u> , <u>Xylolejeunea</u>
Order:	Ptilidiales
Suborder:	Ptilidiineae
Family:	Ptilidiaceae: <u>Ptilidium</u> Neotrichocoleaceae: <u>Neotrichocolea</u> , <u>Trichocoleopsis</u> Herzogianthaceae: <u>Herzogianthus</u>
Order:	Jungermanniales
Suborder:	Personiellineae
Family:	Personiaceae: <u>Personia</u> Schistochilaceae: <u>Gottschea</u> , <u>Paraschistochila</u> , <u>Pachyschistochila</u> , <u>Pluerocladopsis</u> , <u>Schistochila</u>
Suborder:	Lophocoleineae
Family:	Brevianthaceae: <u>Brevianthus</u> Chonecoleaceae: <u>Chonecolea</u> Grolleaceae: <u>Grollea</u> Herbertaceae: <u>Herbertus</u> , <u>Olgantha</u> , <u>Triandrophyllum</u> Lepicoleaceae: <u>Lepicolea</u> Lepidoziaceae: <u>Acromastigum</u> , <u>Amazoopsis</u> , <u>Arachniopsis</u> , <u>Bazzania</u> , <u>Chloranthelia</u> , <u>Dendrobazzania</u> , <u>Drucella</u> , <u>Hyalolepidozia</u> , <u>Hygrolembidium</u> , <u>Isolembidium</u> , <u>Kurzia</u> , <u>Lembidium</u> , <u>Lepidozia</u> ,

(continued)

Table 1.1 (continued)

	<i>Mastigopelma</i> , <i>Megalembidium</i> , <i>Micropterygium</i> , <i>Monodactylopsis</i> , <i>Neogrollea</i> , <i>Odontoseries</i> , <i>Paracromastigum</i> , <i>Protocephaloza</i> , <i>Pseudocephaloza</i> , <i>Psiloclada</i> , <i>Pteropsiella</i> , <i>Sprucella</i> , <i>Telaranea</i> , <i>Zoopsidella</i> , <i>Zoopsis</i>
	Lophocoleaceae: <i>Amphilophocolea</i> , <i>Austrolembidium</i> , <i>Campanocolea</i> , <i>Chiloscyphus</i> , <i>Clasmatocolea</i> , <i>Conoscyphus</i> , <i>Cyanolophocolea</i> , <i>Evansianthus</i> , <i>Hepatostolonophora</i> , <i>Heteroscyphus</i> , <i>Lamellocolea</i> , <i>Leptophyllopsis</i> , <i>Leptoscyphopsis</i> , <i>Leptoscyphus</i> , <i>Lophocolea</i> , <i>Pachyglossa</i> , <i>Perdusenina</i> , <i>Physotheca</i> , <i>Pigafettoa</i> , <i>Platycaulis</i> , <i>Pseudolophocolea</i> , <i>Stolonivector</i> , <i>Tetracymbaliella</i> , <i>Xenocephaloza</i>
	Mastigophoraceae: <i>Dendromastigophora</i> , <i>Mastigophora</i>
	Phycolepidoziaceae: <i>Phycolepidozia</i>
	Plagiochilaceae: <i>Acrochila</i> , <i>Chiastocaulon</i> , <i>Pedinophyllopsis</i> , <i>Pedinophyllum</i> , <i>Plagiochila</i> , <i>Plagiochilidium</i> , <i>Plagiochilion</i> , <i>Proskauera</i> , <i>Rhodoplagiochila</i> , <i>Steeerochila</i> , <i>Szweykowskia</i> , <i>Xenochila</i>
	Pseudolepicoleaceae: <i>Archeophylla</i> , <i>Blepharostoma</i> , <i>Chaetocolea</i> , <i>Hertzogiaria</i> , <i>Isophyllaria</i> , <i>Pseudolepicolea</i> , <i>Archeochaete</i> , <i>Lophochaeta</i> , <i>Temnoma</i>
	Trichocoleaceae: <i>Eotrichocolea</i> , <i>Leiomitra</i> , <i>Trichocolea</i>
	Vetaformaceae: <i>Vetaforma</i>
Suborder:	Cephaloziineae
Family:	Adelanthaceae: <i>Adelanthus</i> , <i>Calyptrocolea</i> , <i>Pseudomarsupidium</i> , <i>Wettsteinia</i>
	Cephaloziellaceae: <i>Allisoniella</i> , <i>Amphicephaloza</i> , <i>Cephalojonesia</i> , <i>Cephalomitron</i> , <i>Cephaloziella</i> , <i>Cephaloziopsis</i> , <i>Cylindrocolea</i> , <i>Gymnocoleopsis</i> , <i>Kymatocalyx</i> , <i>Protomarsupella</i> , <i>Stenorrhypis</i>
	Cephaloziaceae: <i>Alobiella</i> , <i>Alobiellopsis</i> , <i>Anomoclada</i> , <i>Apotomanthus</i> , <i>Cephaloza</i> , <i>Cladopodiella</i> , <i>Fuscocephaloziopsis</i> , <i>Haesselia</i> , <i>Hygrobiella</i> , <i>Iwatsukia</i> , <i>Metahygrobiella</i> , <i>Nowellia</i> , <i>Odontoschisma</i> , <i>Pleurocladula</i> , <i>Schiffneria</i> , <i>Schofieldia</i> , <i>Trabacellula</i>
	Jamesoniellaceae: <i>Anomacaulis</i> , <i>Cryptochila</i> , <i>Cuspidatula</i> , <i>Denotarisia</i> , <i>Jamesoniella</i> , <i>Nothostrepta</i> , <i>Pisanoa</i> , <i>Protosyzygiella</i> , <i>Syzygiella</i>
	Scapaniaceae: (including Chaetophyllopsidaceae and Lophoziaaceae); <i>Anastrepta</i> , <i>Anastrophyllum</i> , <i>Andrewsianthus</i> , <i>Barbilophozia</i> , <i>Cephalolobus</i> , <i>Chaetophyllopsis</i> , <i>Chandonanthus</i> , <i>Diplophyllum</i> , <i>Douinia</i> , <i>Gerhildia</i> , <i>Gymnocolea</i> , <i>Hattoria</i> , <i>Isopaches</i> , <i>Krunodiplophyllum</i> , <i>Lophozia</i> , <i>Macrodiplrophyllum</i> , <i>Plicanthus</i> , <i>Pseudocephaloziella</i> , <i>Roivainenina</i> , <i>Scapania</i> , <i>Scapaniella</i> , <i>Schistochilopsis</i> , <i>Sphenolobopsis</i> , <i>Sphenolobus</i> , <i>Tetralophozia</i> , <i>Tritomaria</i>
Suborder:	Jungermanniiineae
Family:	Acrobolbaceae: <i>Acrobolbus</i> , <i>Austrolophozia</i> , <i>Enigmella</i> , <i>Goebelobryum</i> , <i>Lethocolea</i> , <i>Marsupidium</i> , <i>Tylimanthus</i>
	Antheliaceae: <i>Anthelia</i>
	Arnellaceae: <i>Arnellia</i> , <i>Gongylanthus</i> , <i>Southbya</i> , <i>Stephaniella</i> , <i>Stephaniellidium</i>
	Balantiopsidaceae: <i>Anisotachis</i> , <i>Acroscyphella</i> (= <i>Austroscyphus</i>), <i>Balantiopsis</i> , <i>Eoisotachis</i> , <i>Hypoisotachis</i> , <i>Isotachis</i> , <i>Neesioscyphus</i> , <i>Ruizanthus</i>
	Calypogeaceae: <i>Calypogeia</i> , <i>Eocalypogeia</i> , <i>Metacalypogeia</i> , <i>Mnioloma</i>
	Delavayellaceae: <i>Delavayella</i>

(continued)

Table 1.1 (continued)

Geocalycaceae:	<u>Geocalyx</u> , <u>Harpanthus</u> , <u>Saccogyna</u> , <u>Saccogynidium</u>
Gymnomitriaceae:	<u>Acrolophozia</u> , <u>Anomarsupella</u> , <u>Apomarsupella</u> , <u>Eremonotus</u> , <u>Gymnomitrium</u> , <u>Herzogobryum</u> , <u>Lophonardia</u> , <u>Marsupella</u> , <u>Nanomarsupella</u> , <u>Nothogymnomitrium</u> , <u>Paramomitrium</u> , <u>Poeltia</u> , <u>Prasanthus</u>
Gyrothyraceae:	<u>Gyrothyra</u>
Jackiellaceae:	<u>Jackiella</u>
Jungermanniaceae:	<u>Arctoscyphus</u> , <u>Bragginsella</u> , <u>Cryptocolea</u> , <u>Cryptocoleopsis</u> , <u>Cryptostipula</u> , <u>Diplocolea</u> , <u>Gottschelia</u> , <u>Horikawaella</u> , <u>Jungermannia</u> , <u>Nardia</u> , <u>Notoscyphus</u> , <u>Plectocolea</u> , <u>Scaphophyllum</u> , <u>Solenostoma</u> , <u>Vanaea</u>
Mesoptychiaceae:	<u>Hattoriella</u> , <u>Leiocolea</u> , <u>Liochlaena</u> , <u>Mesoptychia</u>
Myliaaceae:	<u>Leiomylia</u> , <u>Mylia</u>
Trichotemnmataceae:	<u>Trichotemnoma</u>

^aThe genera underlined have been investigated chemically since 1956

Table 1.2 Classification of the Bryophyta (258)**Superclass I**

Class:	Takakiopsida
Order:	Takakiales
Family:	Takakiaceae: <u>Takakia</u> ^a

Superclass II

Class:	Sphagnopsida
Order:	Sphagnales
Family:	Sphagnaceae: <u>Sphagnum</u>
Order:	Ambuchananiales
Family:	Ambuchananiaceae: <u>Ambuchananiia</u>

Superclass III

Class:	Andreaeopsida
Order:	Andreaeales
Family:	Andreaeaceae: <u>Andreaea</u> , <u>Acroschisma</u>

Superclass IV

Class:	Andreaobryopsida
Order:	Andreaobryales
Family:	Andreaobryaceae: <u>Andreaebryum</u>

Superclass V

Class:	Oedipodiopsida
Order:	Oedipodiales
Family:	Oedipodiaceae: <u>Oedipodium</u>
Class:	Polytrichopsida
Order:	Polytrichales
Family:	Polytichaceae: <u>Alophosia</u> , <u>Atrichopsis</u> , <u>Atrichum</u> , <u>Bartramiopsis</u> , <u>Dawsonia</u> , <u>Dendroligotrichum</u> , <u>Herbantia</u> , <u>Itatiella</u> , <u>Lyellia</u> , <u>Meiotichum</u> , <u>Notoligotrichum</u> , <u>Oligotrichum</u> , <u>Plagioraclopus</u> , <u>Pogonatum</u> , <u>Polytrichadelphus</u> , <u>Polytrichastrum</u> , <u>Polytrichum</u> , <u>Pseudatrichum</u> , <u>Psuedoracelopus</u> , <u>Psilopilum</u> , <u>Racelopodopsis</u> , <u>Steereobryon</u>

(continued)

Table 1.2 (continued)

Class:	Tetraphidopsida
Order:	Tetraphidales
Family:	Tetraphidaceae: <i>Tetraphis</i> , <i>Tetrodontium</i>
Class:	Bryopsida
Subclass:	Buxbaumiidae
Order:	Buxbaumiales
Family:	Buxbaumiaceae: <i>Buxbaumia</i>
Subclass:	Diphysciidae
Order:	Diphysciales
Family:	Diphysciaceae: <i>Diphyscium</i>
Subclass:	Timmiidae
Order:	Timmiales
Family:	Timmiaceae: <i>Timmia</i>
Subclass:	Furnariidae
Order:	Gigaspermales
Family:	Gigaspermaceae: <i>Gigaspermum</i> , <i>Chamaebryum</i> , <i>Costesia</i> , <i>Lorentziella</i> , <i>Oedipodiella</i>
Order:	Encalyptales
Family:	Bryobartramiaceae: <i>Bryobartramia</i> Encalyptaceae: <i>Bryobrittonia</i> , <i>Encalypta</i>
Order:	Funariles
Family:	Funariaceae: <i>Aphanorrhagma</i> , <i>Brachymeniopsis</i> , <i>Bryobeckettia</i> , <i>Clavitheca</i> , <i>Cygnicollum</i> , <i>Enthosthodon</i> , <i>Funaria</i> , <i>Funariella</i> , <i>Goniomitrium</i> , <i>Loiseaubryum</i> , <i>Nonamitriella</i> , <i>Physcomitrella</i> , <i>Physcomitrellopsis</i> , <i>Physcomitrium</i> , <i>Pyramidula</i> Disceliaceae: <i>Discelium</i>
Subclass:	Dicranidae
Order:	Scouleriales
Family:	Scouleriaceae: <i>Scouleria</i> , <i>Tridontium</i> Drummondaceae: <i>Drummondia</i>
Order:	Bryoxiphiales
Family:	Bryoxiphiaceae: <i>Bryoxiphium</i>
Order:	Grimmiales
Family:	Grimmiaceae: <i>Bucklandiella</i> , <i>Codriophorus</i> , <i>Dryptodon</i> , <i>Grimmia</i> , <i>Leucoperichaetium</i> , <i>Niphotrichum</i> , <i>Racomitrium</i> , <i>Schistidium</i> Ptychomitriaceae: <i>Aligrimmia</i> , <i>Campylostelium</i> , <i>Indusiella</i> , <i>Jaffueliobryum</i> , <i>Ptychomitriopsis</i> , <i>Ptychomitrium</i> Seligeriaceae: <i>Blindia</i> , <i>Brachydontium</i> , <i>Hymenolomopsis</i> , <i>Seligeria</i> , <i>Trochobryum</i>
Order:	Archidiales
Family:	Archidiaceae: <i>Archidium</i>
Order:	Dicranales
Family:	Fissidentaceae: <i>Fissidens</i> Hypodontiaceae: <i>Hypodontium</i> Eustichiaceae: <i>Eustichia</i> Ditrichaceae: <i>Astomiopsis</i> , <i>Austrophilbertiella</i> , <i>Bryomanginia</i> , <i>Cerotodon</i> , <i>Cheilothea</i> , <i>Chrysoblastella</i> , <i>Cladastomum</i> , <i>Cleistocarpidium</i> , <i>Crumuscus</i> , <i>Cygniella</i> , <i>Distichium</i> , <i>Ditrichopsis</i> , <i>Ditrichum</i> , <i>Ditrichium</i> , <i>Ditrichum</i>

(continued)

Table 1.2 (continued)

	<i>Eccremidium</i> , <i>Garckea</i> , <i>Kleioweisiopsis</i> , <i>Pleuriditrichum</i> , <u><i>Pleuridium</i></u> , <i>Rhamphidium</i> , <i>Saelania</i> , <i>Skottsbergia</i> , <i>Strombulidens</i> , <i>Trichodon</i> , <i>Tristichium</i> , <i>Wilsoniella</i>
	Bruchiaceae: <i>Bruchia</i> , <i>Cladophascum</i> , <i>Eobruchia</i> , <i>Pringleella</i> , <i>Trematodon</i>
	Rhachitheciaceae: <i>Hypnodontopsis</i> , <i>Jonesiobryum</i> , <i>Rhachitheciopsis</i> , <i>Rhachithecium</i> , <i>Tisserantiella</i> , <i>Uleastrum</i> , <i>Zanderia</i>
	Erpodiaceae: <i>Aulacopilum</i> , <i>Erpodium</i> , <i>Solmsiella</i> , <i>Venturiella</i> , <i>Wildia</i>
	Schistostegaceae: <i>Schistostega</i>
	Viridivelleraceae: <i>Viridivellus</i>
	Rhabdoweisiaceae: <u><i>Amphidium</i></u> , <u><i>Cynodontium</i></u> , <u><i>Dichodontium</i></u> , <u><i>Dicraoweisia</i></u> , <u><i>Holodontium</i></u> , <u><i>Oncophorus</i></u> , <i>Oreas</i> , <i>Oreoweisia</i> , <i>Pseudohyophila</i> , <u><i>Rhabdoweisia</i></u> , <i>Symblepharis</i> , <i>Verrucidens</i>
	Dicranaceae: <i>Anisothecium</i> , <i>Aongstroemia</i> , <i>Aongstoemopsis</i> , <i>Arcota</i> , <i>Atractyllocarpus</i> , <i>Braunfelsia</i> , <i>Brotherobryum</i> , <i>Bryotestua</i> , <i>Camptodontium</i> , <i>Chorisodontium</i> , <i>Cnestrum</i> , <i>Cryptodicranum</i> , <u><i>Dicranella</i></u> , <u><i>Dicranoloma</i></u> , <u><i>Dicranum</i></u> , <i>Diobelonela</i> , <i>Eucamptodon</i> , <i>Eucamptodontopsis</i> , <i>Holomitriopsis</i> , <i>Holomitrium</i> , <i>Hygodicranum</i> , <i>Kiaeria</i> , <i>Leptotrichella</i> , <i>Leucoloma</i> , <i>Macrodictyum</i> , <i>Mesotus</i> , <i>Mitrobryum</i> , <i>Muscoherzogia</i> , <u><i>Orthodicranum</i></u> , <u><i>Paraleucobryum</i></u> , <i>Parisia</i> , <i>Pocsiella</i> , <i>Polymerodon</i> , <i>Pseudephemerum</i> , <i>Pseudochorisodontium</i> , <i>Schliephackea</i> , <i>Sclerodontium</i> , <i>Sphaerothecium</i> , <i>Steyermarkiella</i> , <i>Wardia</i> , <i>Werneribryum</i>
	Leucobryaceae: <i>Atractyllocarpus</i> , <i>Brothera</i> , <i>Bryohumbertis</i> , <i>Camphylopodiella</i> , <i>Camphylopus</i> , <i>Cladopodanthus</i> , <i>Dicranodontium</i> , <u><i>Leucobryum</i></u> , <i>Microcampylopus</i> , <i>Ochrobryum</i> , <i>Pilopogon</i> , <i>Schistomitrium</i>
	Calymperaceae: <i>Arthrocormus</i> , <i>Calympres</i> , <i>Exodictyon</i> , <i>Exostratum</i> , <i>Leucophanes</i> , <i>Mitthyridium</i> , <i>Octoblepharum</i> , <i>Syrrophodon</i>
Order:	Pottiaceae
Family:	Pottiaceae: <i>Acaulon</i> , <i>Aloinella</i> , <i>Aloinia</i> , <i>Anoetangium</i> , <i>Aschisma</i> , <i>Barbula</i> , <i>Bellibarbula</i> , <i>Bryocephospora</i> , <i>Bryoerythrophyllum</i> , <i>Calymperastrum</i> , <i>Calyptopogon</i> , <i>Chenia</i> , <i>Chinoloma</i> , <i>Crossidium</i> , <i>Crumia</i> , <i>Dialytrichia</i> , <i>Didymodon</i> , <i>Dolotortula</i> , <i>Ephemerum</i> , <i>Erythrophyllopsis</i> , <u><i>Eucladium</i></u> , <i>Gangulea</i> , <i>Gertrudiella</i> , <i>Globulinella</i> , <i>Goniomitrium</i> , <i>Gymnostomiella</i> , <i>Gymnostomum</i> , <i>Gyroweisia</i> , <i>Hannediella</i> , <i>Hilpertia</i> , <i>Hymenostyliella</i> , <i>Hymenostylium</i> , <i>Hyophila</i> , <i>Hyophiladelphus</i> , <i>Leptobarbula</i> , <i>Leptodontiella</i> , <i>Leptodontium</i> , <i>Luisierella</i> , <i>Microbryum</i> , <i>Micromitrium</i> , <i>Mironia</i> , <i>Molendia</i> , <i>Nanomitriopsis</i> , <i>Neophoenix</i> , <i>Pachyneuropsis</i> , <i>Phascopsis</i> , <i>Plaubelia</i> , <i>Pleurochaete</i> , <i>Pottiopsis</i> , <i>Pseudocrossidium</i> , <i>Pseudosymblepharis</i> , <i>Pterygoneurum</i> , <i>Quaesticula</i> , <i>Reimersia</i> , <i>Rhexophyllum</i> , <i>Sagenotortula</i> , <i>Saitobryum</i> , <i>Sarconeuron</i> , <u><i>Scopelophila</i></u> , <i>Splachnobryum</i> , <i>Stegonia</i> , <i>Stonea</i> , <i>Streptocalyptra</i> , <i>Streptopogon</i> , <i>Streptotrichum</i> , <i>Syntrichia</i> , <i>Teniolophora</i> , <i>Tetracosindon</i> , <i>Tetrapterum</i> , <i>Timmia</i> , <i>Tortella</i> , <u><i>Tortula</i></u> , <i>Trachycapidium</i> , <i>Trachydontium</i> , <i>Trichostomum</i> , <i>Triquetrella</i> , <i>Tuerckheimia</i> , <i>Uleobryum</i> , <i>Weisiopsis</i> , <i>Weissiodicranum</i> , <i>Willia</i>
	Pleurophascaceae: <i>Pleurophascum</i>
	Sepotortellaceae: <i>Sepotortella</i>
	Mitteniaceae: <i>Mittenia</i>
Subclass:	Bryidae
Superorder:	Bryanae
Order:	Splachnales

(continued)

Table 1.2 (continued)

Family:	Splachnaceae: <u>Aplodon</u> , <u>Moseniella</u> , <u>Splachnum</u> , <u>Tayloria</u> , <u>Tetraplodon</u> , <u>Voitia</u>
	Meesiaceae: <u>Amblyodon</u> , <u>Leptobryum</u> , <u>Meesia</u> , <u>Neomeesia</u> , <u>Paludella</u>
Order:	Bryales
Family:	Catoscopiaceae: <u>Catoscopium</u>
	Pulchrinodaceae: <u>Pulchrinodus</u>
	Bryaceae: <u>Acidodontium</u> , <u>Anomobryum</u> , <u>Brachymenium</u> , <u>Bryum</u> , <u>Leptobryum</u> , <u>Leucobryum</u> , <u>Mniobryoides</u> , <u>Personia</u> , <u>Pohlia</u> , <u>Ptychostromum</u> , <u>Rhodobryum</u> , <u>Roellia</u> , <u>Rosulabryum</u>
	Phyllodrepaniaceae: <u>Mniomalia</u> , <u>Phyllodrepanium</u>
	Pseudoditrichaceae: <u>Pseudoditrichum</u>
	Mniaceae: <u>Cinclidium</u> , <u>Cyrtomnium</u> , <u>Epipterygium</u> , <u>Leucolepsis</u> , <u>Mielichhoferia</u> , <u>Mnium</u> , <u>Ochiobryum</u> , <u>Orthomnion</u> , <u>Plagiomnium</u> , <u>Pseudobryum</u> , <u>Pseudopohlia</u> , <u>Rhizomnium</u> , <u>Schizymenium</u> , <u>Synthetodontium</u> , <u>Trachycystis</u>
	Leptostomataceae: <u>Leptostomum</u>
Order:	Bartramiales
Family:	Bartramiaceae: <u>Anacolia</u> , <u>Bartramia</u> , <u>Breutelia</u> , <u>Conostomum</u> , <u>Fleischerobryum</u> , <u>Flowersia</u> , <u>Leiomela</u> , <u>Neosharpiella</u> , <u>Philontis</u> , <u>Plagiopus</u>
Order:	Orthotrichales
Family:	Orthotrichaceae: <u>Amphidium</u> , <u>Cardotiella</u> , <u>Ceuthotheca</u> , <u>Codonoblepharon</u> , <u>Desmotheca</u> , <u>Florschuetziella</u> , <u>Groutiella</u> , <u>Leratia</u> , <u>Macrocoma</u> , <u>Macromitrium</u> , <u>Matteria</u> , <u>Orthotrichum</u> , <u>Pentastichella</u> , <u>Pleurothotrichum</u> , <u>Schlotheimia</u> , <u>Sehnemobryum</u> , <u>Steneobryum</u> , <u>Ulotia</u> , <u>Zygodon</u>
Order:	Hedwigiales
Family:	Hedwigiaceae: <u>Braunia</u> , <u>Bryowijkia</u> , <u>Hedwigia</u> , <u>Hedwigidium</u> , <u>Pseudobraunia</u>
	Helicophyllaceae: <u>Helicophyllum</u>
	Rhacocarpaceae: <u>Parahacocarpus</u> , <u>Rhacocarpus</u>
Order:	Rhizogoniales
Family:	Rhizogoniaceae: <u>Colomnion</u> , <u>Cryptopodium</u> , <u>Goniobryum</u> , <u>Pyrrhobryum</u> , <u>Rhizogonium</u>
	Aulacomniaceae: <u>Aulocomnium</u>
	Orthodontiaceae: <u>Orthodontiym</u> , <u>Orthodontopsis</u>
Superorder:	Hypnanae
Order:	Hypnodendrales
Family:	Braithwaiteaceae: <u>Braithwaitea</u>
	Racopilaceae: <u>Powellia</u> , <u>Racopilum</u>
	Pterobryellaceae: <u>Cyrtopodendron</u> , <u>Pterobryella</u> , <u>Sciadocladus</u>
	Hypnodendraceae: <u>Bescherellia</u> , <u>Cyrtopus</u> , <u>Dendro-hypnum</u> , <u>Franciella</u> , <u>Hypnodendron</u> , <u>Mniodendron</u> , <u>Spiridens</u> , <u>Touwiodendron</u>
Order:	Ptychomniales
Family:	Ptychomniaceae: <u>Cladomnion</u> , <u>Cladomniopsis</u> , <u>Dichelodontium</u> , <u>Endotrichellopsis</u> , <u>Euptychium</u> , <u>Garovaglia</u> , <u>Glyphotheciopsis</u> , <u>Glyphothecium</u> , <u>Hampeella</u> , <u>Ombronesus</u> , <u>Ptychomniella</u> , <u>Ptychomnion</u> , <u>Tetraphidopsis</u>

(continued)

Table 1.2 (continued)

Order:	Hookeriales
Family:	Hypopterygiaceae: <i>Arbusculohypopterygium</i> , <i>Canalohypopterygium</i> , <i>Catharomnion</i> , <i>Cyathophorum</i> , <i>Dendrocypophorum</i> , <i>Dendrohypopterygium</i> , <i>Hypopterygium</i> , <i>Lopidium</i>
	Saulomataceae: <i>Ancistrodes</i> , <i>Sauloma</i> , <i>Vesiculariopsis</i>
	Daltoniaceae: <i>Achrophyllum</i> , <i>Adelothecium</i> , <i>Benitotania</i> , <i>Bryobrothera</i> , <i>Calypstrochaeta</i> , <i>Daltonia</i> , <i>Distichophyllidium</i> , <i>Distichophyllum</i> , <i>Ephemeropsis</i> , <i>Leskeodon</i> , <i>Leskodontopsis</i> , <i>Metadistichophyllum</i>
	Schimperobryaceae: <i>Schimperobryum</i>
	Hookeriaceae: <i>Crossomitrium</i> , <i>Hookeria</i>
	Leucomiaceae: <i>Leucomium</i> , <i>Rhynchostegiopsis</i> , <i>Tetrastichium</i>
	Pilotrichaceae: <i>Actinodontium</i> , <i>Amblytropis</i> , <i>Brymela</i> , <i>Callicostella</i> , <i>Callicostellopsis</i> , <i>Cyclodictyon</i> , <i>Diploneuron</i> , <i>Helicoblepharum</i> , <i>Hermiragis</i> , <i>Hookeriopsis</i> , <i>Hypnella</i> , <i>Lepidopilidium</i> , <i>Lepidopilum</i> , <i>Neohypnella</i> , <i>Pilotrichidium</i> , <i>Pilotrichum</i> , <i>Stenodesmus</i> , <i>Stenodictyon</i> , <i>Thamniopsis</i> , <i>Trachyxiphium</i>
Order:	Hypnales
Family:	Rutenbergiaceae: <i>Neorutenbergia</i> , <i>Pseudocryphaea</i> , <i>Rutenbergia</i>
	Trachylomataceae: <i>Trachyloma</i>
	Fontinalaceae: <i>Brachelyma</i> , <i>Dichelyma</i> , <i>Fontinalis</i>
	Climaciaceae: <i>Climacium</i> , <i>Pleuroziopsis</i>
	Amblystegiaceae: <i>Amblystegium</i> , <i>Anacamptodon</i> , <i>Bryosteimannia</i> , <i>Campyliadelphus</i> , <i>Camphyllum</i> , <i>Conardia</i> , <i>Cratoneuron</i> , <i>Cratoneurosis</i> , <i>Drepanocladus</i> , <i>Gradsteinia</i> , <i>Hygroamblystegium</i> , <i>Hygrohypnella</i> , <i>Hygrohypnum</i> , <i>Hypnobartlettia</i> , <i>Koponenia</i> , <i>Leptodictyum</i> , <i>Limbella</i> , <i>Limprichtia</i> , <i>Ochyraea</i> , <i>Palustriella</i> , <i>Pictus</i> , <i>Pseudocalliergon</i> , <i>Pseudohygrohypnum</i> , <i>Sanionia</i> , <i>Sasaokaea</i> , <i>Sciaromiella</i> , <i>Sciaromiopsis</i> , <i>Scorpidium</i> , <i>Sinocalliergon</i> , <i>Serpoleskea</i> , <i>Vittia</i>
	Calliergonaceae: <i>Calliergon</i> , <i>Hamatocaulis</i> , <i>Loeskyppnum</i> , <i>Straminergon</i> , <i>Warnstorfia</i>
	Helodiaceae: <i>Actinotuidium</i> , <i>Bryochena</i> , <i>Helodium</i>
	Rigodiaceae: <i>Rigodium</i>
	Leskeaceae: <i>Claopodium</i> , <i>Fabronidium</i> , <i>Haplocladium</i> , <i>Hylocomiopsis</i> , <i>Leptocladium</i> , <i>Leptopterigynandrum</i> , <i>Lescuraea</i> , <i>Leskea</i> , <i>Leaskeadelphus</i> , <i>Leskeella</i> , <i>Lindbergia</i> , <i>Mamillariella</i> , <i>Miyabea</i> , <i>Orthoamblystegium</i> , <i>Platylomella</i> , <i>Pseudoleskea</i> , <i>Pseudoleskeella</i> , <i>Pseudoleskeopsis</i> , <i>Ptychodium</i> , <i>Rigodiadelphus</i> , <i>Schwetschkea</i>
	Thuidiaceae: <i>Abietinella</i> , <i>Boulaya</i> , <i>Cyrto-hypnum</i> , <i>Fauriella</i> , <i>Pelekium</i> , <i>Rauiella</i> , <i>Thuidiopsis</i> , <i>Thuidium</i>
	Regmatodontaceae: <i>Regmatodon</i>
	Stereophyllaceae: <i>Catogoniopsis</i> , <i>Entodontopsis</i> , <i>Eulacophyllum</i> , <i>Juratzkaea</i> , <i>Pilosium</i> , <i>Sciuroleska</i> , <i>Stenocaridium</i> , <i>Stereophyllum</i>
	Brachytectiaceae: <i>Aerobryum</i> , <i>Aerolindigia</i> , <i>Brachytectiastrum</i> , <i>Brachytectium</i> , <i>Bryhnia</i> , <i>Bryoandersonia</i> , <i>Cirriphyllum</i> , <i>Clasmatodon</i> , <i>Donrichardsia</i> , <i>Eriodon</i> , <i>Eurhynchiadelphus</i> , <i>Eurhynchiastrum</i> , <i>Eurhynchiella</i> , <i>Eurhynchium</i> , <i>Flabellidium</i> , <i>Helicodontium</i> , <i>Homalotheciella</i> , <i>Homalothecium</i> , <i>Juratzkaeella</i> , <i>Kindbergia</i> , <i>Lindigia</i> , <i>Mandoniella</i> , <i>Meteoridium</i> , <i>Myuroclada</i> , <i>Nobregaea</i> , <i>Okamuraea</i> , <i>Oxyrrhynchium</i> , <i>Palamocladium</i> , <i>Plasteurhynchium</i> , <i>Platyhypnidium</i> , <i>Pseudopleuropus</i> , <i>Pseudoscleropodium</i> , <i>Remyella</i> , <i>Rhynchostegiella</i> ,

(continued)

Table 1.2 (continued)

	<i>Rhynchostegium</i> , <i>Schimperella</i> , <i>Sciuro-hypnum</i> , <u><i>Scleropodium</i></u> , <i>Scorpiurium</i> , <i>Squamidium</i> , <i>Stenocarpidiopsis</i> , <i>Tomentypnum</i> , <i>Zelometeorium</i>
Meteoriaceae:	<i>Aerobryidium</i> , <i>Aerobryopsis</i> , <i>Barbella</i> , <i>Barbellopsis</i> , <i>Chrysocladium</i> , <i>Cryptopapillaria</i> , <i>Diaphanodon</i> , <i>Duthiella</i> , <i>Floribundaria</i> , <i>Lepyrodontopsis</i> , <i>Meteoriopsis</i> , <i>Meteorium</i> , <i>Neodicladiella</i> , <i>Neonoguchia</i> , <i>Pseudospiridentopsis</i> , <i>Pseudotrachypus</i> , <i>Sinskea</i> , <i>Toloxis</i> , <i>Trachycladiella</i> , <i>Trachypodopsis</i> , <i>Trachypus</i> , <u><i>Weymouthia</i></u>
Myriniaceae:	<i>Austinia</i> , <i>Macgregorella</i> , <i>Merrillibryum</i> , <i>Myrinia</i> , <i>Nematocladia</i>
Fabroniaceae:	<i>Dimerodontium</i> , <i>Fabronia</i> , <i>Ischyrodon</i> , <i>Lieverella</i> , <i>Rhizofabronia</i>
Hypnaceae:	<i>Acridoton</i> , <i>Andoa</i> , <i>Bardunovia</i> , <i>Breidleria</i> , <i>Bryocrumia</i> , <i>Buckiella</i> , <i>Callicladium</i> , <i>Calliergonella</i> , <i>Campylophyllopsis</i> , <u><i>Camphyllum</i></u> , <i>Camphyliidium</i> , <i>Camphylophyllum</i> , <i>Caribaehypnum</i> , <i>Chryso-hypnum</i> , <i>Crepidophyllum</i> , <i>Ctenidiadalplus</i> , <i>Cyathothecium</i> , <i>Ectropotheciella</i> , <i>Ectropotheciopsis</i> , <i>Ectropothecium</i> , <i>Elharveya</i> , <i>Elmeriobryum</i> , <i>Endontella</i> , <i>Eurohypnum</i> , <i>Fareauella</i> , <i>Gammiella</i> , <i>Giraldiella</i> , <i>Gollania</i> , <i>Hageniella</i> , <u><i>Herzogiella</i></u> , <i>Homomallium</i> , <i>Hondaella</i> , <i>Horridohypnum</i> , <i>Hycomium</i> , <u><i>Hypnum</i></u> , <i>Irelandia</i> , <i>Isopterygiopsis</i> , <i>Leiodontium</i> , <i>Leptoischyrodon</i> , <i>Macrothamniella</i> , <i>Mahua</i> , <i>Microcteidium</i> , <i>Mittenothamnium</i> , <i>Nanothecium</i> , <i>Orthothecium</i> , <i>Phyllodon</i> , <i>Plagiotheciopsis</i> , <i>Platydictya</i> , <i>Platygyriella</i> , <i>Podperaea</i> , <i>Psaudohypnella</i> , <i>Pseudotaxiphyllum</i> , <i>Ptilium</i> , <i>Pylaisia</i> , <i>Rhacopilopsis</i> , <i>Rhizohypnella</i> , <i>Sclerohypnum</i> , <i>Stenotheciopsis</i> , <i>Stereodon</i> , <i>Stereodontopsis</i> , <i>Syringothecium</i> , <i>Taxiphyllopsis</i> , <u><i>Taxiphyllum</i></u> , <i>Tripterocladium</i> , <u><i>Vesicularia</i></u> , <i>Wijkella</i>
Catagoniaceae:	<i>Catagonium</i>
Pterigyantraceae:	<i>Hordon</i> , <i>Heterocladium</i> , <i>Iwatusukiella</i> , <i>Myurella</i> , <i>Pterigynandrum</i> , <i>Trachyphyllum</i>
Hylocomiaceae:	<i>Ctenidium</i> , <i>Hylocomiastrum</i> , <u><i>Hylocomium</i></u> , <i>Leptocladiaella</i> , <i>Leptothymenium</i> , <i>Leskeobryum</i> , <i>Macrothamnium</i> , <i>Meteoriella</i> , <i>Neodolichomitra</i> , <i>Orontobryum</i> , <u><i>Pleurozium</i></u> , <i>Puiggariopsis</i> , <u><i>Rhytidiadelphus</i></u> , <i>Rhytidiopsis</i> , <i>Schofieldiella</i>
Rhytidiaceae:	<i>Rhytidium</i>
Symphyodontaceae:	<i>Chaetomitriopsis</i> , <i>Chaetomitrium</i> , <i>Dimorphocladon</i> , <i>Symphyodon</i> , <i>Trachythecium</i> , <i>Unclejackia</i>
Plagiotheciaceae:	<u><i>Plagiothecium</i></u>
Entodontaceae:	<u><i>Entodon</i></u> , <i>Erythrodontium</i> , <i>Mesondon</i> , <i>Pylaisiobryum</i>
Pylaisiadelphaceae:	<i>Aptychella</i> , <u><i>Brotherella</i></u> , <i>Clastobryopsis</i> , <i>Clastobryum</i> , <i>Heterophyllum</i> , <i>Isocladiaella</i> , <i>Isopterygium</i> , <i>Mastopoma</i> , <i>Platygyrium</i> , <i>Pseudotrismegista</i> , <i>Pterogonidium</i> , <i>Pylaisiadelpha</i> , <i>Taxitheliella</i> , <i>Taxithelium</i> , <i>Trismegista</i> , <u><i>Wijkia</i></u>
Sematophyllaceae:	<i>Acanthorrhynchium</i> , <i>Acroporium</i> , <i>Allionellopsis</i> , <i>Aptychiopsis</i> , <i>Chinostomum</i> , <i>Clastobryella</i> , <i>Clastobryophyllum</i> , <i>Colobodontium</i> , <i>Doniella</i> , <i>Hydropogon</i> , <i>Hydropogonella</i> , <i>Macrohymenium</i> , <i>Meiotheciella</i> , <i>Meiothecium</i> , <i>Papillidiopsis</i> , <i>Paranapiacabaea</i> , <i>Potamium</i> , <i>Pterogoniopsis</i> , <i>Piloecium</i> , <i>Radulina</i> , <i>Rhaphidostichum</i> , <i>Schraderella</i> , <i>Schroeterella</i> , <i>Sematophyllum</i> , <i>Timotimius</i> , <i>Trichosteleum</i> , <i>Trolliella</i> , <i>Warburgiella</i>

(continued)

Table 1.2 (continued)

Cryphaeaceae: <i>Cryphaea</i> , <i>Cryphaeophilum</i> , <i>Cryphidium</i> , <i>Cyptodon</i> , <i>Cyptodontopsis</i> , <i>Dendroalsia</i> , <i>Dendrocryphaea</i> , <i>Dendropogonella</i> , <i>Pilotrichopsis</i> , <i>Schoenobryum</i> , <i>Sphaerotheciella</i>
Prionodontaceae: <i>Prionodon</i>
Leucodontaceae: <u><i>Antitrichia</i></u> , <i>Dozya</i> , <i>Eoleucodon</i> , <i>Felipponea</i> , <i>Leucodon</i> , <i>Pterogonium</i> , <i>Scabridens</i>
Pterobryaceae: <i>Calyptothecium</i> , <i>Cryptogonium</i> , <i>Henicodium</i> , <i>Hildebrandtiella</i> , <i>Horikawea</i> , <i>Jaegeria</i> , <i>Micralsopsis</i> , <i>Muellerobryum</i> , <i>Neolindbergia</i> , <i>Orthorrhynchidium</i> , <i>Orthostichidium</i> , <i>Orthostichopsis</i> , <i>Ostewaldiella</i> , <i>Penziella</i> , <i>Pireella</i> , <i>Psuedopterobryum</i> , <i>Pterobryidium</i> , <i>Pterobryon</i> , <i>Pterobryopsis</i> , <i>Renauldia</i> , <i>Rhabdodontium</i> , <i>Spiridentopsis</i> , <i>Smpphysodon</i> , <i>Symphysodontella</i>
Phyllogoniaceae: <i>Phyllogonium</i>
Orthorrhynchiaceae: <i>Orthorrhynchium</i>
Lepyrodontaceae: <i>Lepyrodon</i>
Neckeraceae: <i>Baldwiniella</i> , <i>Bissetia</i> , <i>Btyolawtonia</i> , <i>Caduciella</i> , <i>Crassiphylm</i> , <i>Cryptolepton</i> , <i>Curviciadium</i> , <i>Dixonia</i> , <u><i>Dolichomitra</i></u> , <i>Handeliobryum</i> , <i>Himantocladium</i> , <u><i>Homalia</i></u> , <i>Homalidelphus</i> , <i>Homalidendron</i> , <i>Hydrocryphea</i> , <i>Isodrepanium</i> , <i>Metaneckera</i> , <u><i>Neckera</i></u> , <i>Neckeropsis</i> , <i>Neomacounia</i> , <i>Noguchiodendron</i> , <i>Pendulothecium</i> , <i>Pinnatella</i> , <i>Porotrichodendron</i> , <i>Porotrichopsis</i> , <i>Porotrichum</i> , <u><i>Thamnum</i></u> , <u><i>Thamnobryum</i></u> , <i>Touwia</i>
Echinodiaceae: <i>Echinodium</i>
Leptodontaceae: <i>Alsia</i> , <i>Forsstroemia</i> , <i>Leptodon</i> , <i>Taiwanobryum</i>
Lembophyllaceae: <i>Acrocladium</i> , <i>Camptochaete</i> , <u><i>Dolichomitra</i></u> , <i>Dolichomitriopsis</i> , <i>Fallaciella</i> , <i>Fifea</i> , <u><i>Isothecium</i></u> , <i>Lembophyllum</i> , <i>Neobarbella</i> , <i>Orthostichella</i> , <i>Pilotrichella</i> , <i>Weymouthia</i>
Myuriaceae: <i>Eumyurium</i> , <i>Myurium</i> , <i>Oediciadium</i> , <i>Palisadula</i>
Anomodontaceae: <i>Anomodon</i> , <i>Bryonorrissia</i> , <i>Chileobryon</i> , <i>Curviramea</i> , <i>Haplohymenium</i> , <i>Herpetineuron</i> , <i>Schwetschkeopsis</i>
Theliaceae: <i>Thelia</i>
Microtheciellaceae: <i>Microtheciella</i>
Sorapillaceae: <i>Sorapilla</i>

^aThe genera underlined have been investigated chemically since 1956

Table 1.3 Classification of the Anthocerotophyta (676)

Class:	Leiosporocerotopsida
Order:	Leiosporocerotales
Family:	Leiosporocerotaceae: <i>Leiosporoceros</i>
Class:	Anthocerotopsida
Subclass:	Anthocerotidae
Order:	Anthocerotales
Family:	Anthocerotaceae: <u><i>Anthoceros</i></u> ^a , <i>Folioceros</i> , <i>Sphaerosporoceros</i>
Subclass:	Notothylatidae
Order:	Notothyladales
Family:	Notothyladaceae: <u><i>Notothylas</i></u> , <u><i>Phaeoceros</i></u> , <i>Paraphymatoceros</i> , <i>Hattoriceros</i> , <i>Mesoceros</i>
Subclass:	Dendrocerotidae
Order:	Phymatocerales
Family:	Phymatocerotaceae: <i>Phymatoceros</i>
Order:	Dendrocerotales
Family:	Dendrocerotaceae
	Dendrocerotoideae: <u><i>Dendroceros</i></u> , <u><i>Megaceros</i></u> , <u><i>Nothoceros</i></u>
Subfamily:	Phaeomegacerotoideae: <u><i>Phaeomegaceros</i></u>

^aThe genera underlined have been investigated chemically since 1958

2 Biodiversity of Bryophytes

The Marchantiophyta (liverworts) includes three classes, the Haplomitriopsida, Marchantiopsida, and Jungermanniopsida, and 15 orders, 82 families, 316 genera (Table 1.1), and 6,000 species. These small plant groups are distributed nearly everywhere in the world. New species are still being recorded in the literature. There are 54 endemic genera in countries of the southern hemisphere, such as New Zealand and Argentina, as shown in Fig. 2.1 (364). In Asia including Japan, a relatively large number of endemic genera (21) have been recorded, but Europe, North America, and Africa including Madagascar are quite poor regions for endemic genera. The richness of the endemic genera of bryophytes in the southern hemisphere suggests that the bryophytes might have originated in the past from what is now Antarctica some 350,000,000 years ago and then they were introduced to the northern hemisphere during a long-range evolutionary process. In Japan, Yaku Island is considered an important place to locate bryophyte species. In the southern hemisphere, New Zealand is one of the best countries to observe many different species of the Marchantiophyta, which are totally different from those found in Japan.

Notably, countries displaying the highest species density of liverworts with over 250 species per 10,000 km², include New Zealand, New Caledonia, Japan (615 species each), and Costa Rica (561). Areas or countries with more than 151 species per 10,000 km² include Nepal (353 species), Bhutan (277), Taiwan (498), the Philippines (514), the island of Borneo (608), Colombia (752), Ecuador (606), and Sao Paulo province in Brazil (472). French Guyana, Norway, the British Isles, Madagascar, and the Iberian Peninsula are also rich areas for liverworts, with 75–150 species per 10,000 km² (437).

In Siberia (Russia), 280 liverworts have been recorded, and, of those known at present from Siberia, about 71% are found as widespread species of circumpolar or semi-circumpolar distribution. Only five species are known to be endemic to Siberia. The most commonly encountered liverwort in this region is *Scapania rufidula* (438).

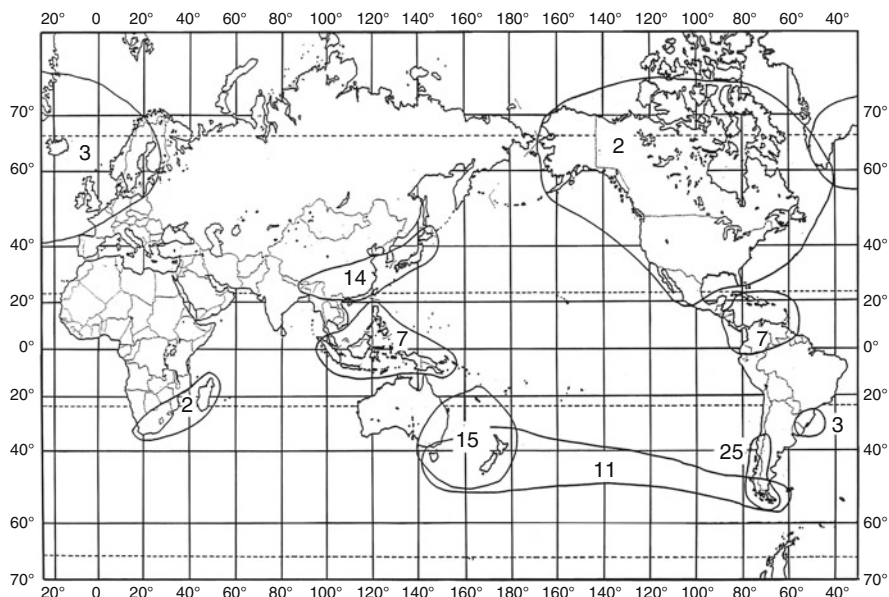


Fig. 2.1 Number of endemic genera of bryophytes

India and Sri Lanka are also rich source countries of liverworts and 555 and 110 species have been recorded, respectively. In Nepal and Bhutan, in turn, 36 and 44 taxa of liverworts are known (154).

Research on the distribution of liverworts in the Great Himalayan National Park was carried out by Singh and Singh, and the presence of 92 species in over 39 genera and 23 families was recorded (758). This accounts for about 11.3% of the total Indian liverworts and hornworts in just 0.04% of its geographical region.

Liverwort diversity at the summit of Khao Nan, Khao Nan National Park, Nakhon Si Thammarat Province, Thailand, has been investigated by Sukkharak and associates. A total of 547 specimens were collected, accounting for 103 species in 40 genera and 17 families. Among the 40 genera of liverworts studied, *Frullania*, *Radula*, *Plagiochila*, *Bazzania*, and *Drepanolejeunea* species were represented by the largest number of species (786).

Iwatsuki listed 332 genera and 1,135 species of mosses occurring in Japan (368). Thus, Japan is rich in moss species. Anderson and coworkers reported that there are 1,320 species of mosses from North America. The area of Japan is about 370,000 km² and hence only 1/48 of the area of North America (29).

In Mongolia, 442 species of mosses from 152 genera and 38 families have been reported, and their distribution pattern resembles that of Siberia (904).

Mainland China (genera/species: 409/1,835), Taiwan (278/835), Indochina (249/953), West Malaysia and Singapore (145/466), Sulawesi (144/340), Java (204/566), Sumatra (8,163/489), Borneo (190/673), Papua New Guinea (263/918), the Lesser Sunda Islands (162/368) and the Philippines (246/743) are also rich in mosses (473).

In tropical regions such as Borneo, Sumatra, and Papua New Guinea, there are rain forests where many liverwort species have been found. However, different species like those in the Lejeuneaceae family are intermingled with one another, so it is time-consuming work to adequately separate and document these. In Ecuador and Colombia, bryophyte species grow preferentially at altitudes above 2,000 m. In Table 1.1, each subclass, order, family, and genus of the Marchantiophyta is shown. Each underlined genus is that chemically studied since 1956.

3 Chemical Diversity of Bryophytes

3.1 Typical Components of Bryophytes

Most of the secondary metabolites found in liverworts are lipophilic mono-, sesqui-, and diterpenoids as well as small aromatic compounds. In recent years, several hundred additional new compounds of this type have been isolated from bryophytes and their structures elucidated (39, 40, 45).

Liverworts are abundant sources of new carbon skeletons of natural sesquiterpenoids, inclusive of *seco*-africanes (103–105), nor-*seco*-africanes (106, 107), noraristolanes (115–117), 1,10-*seco*-aromadendranes (146–154), aromadendrane-guaiane dimers (177), 2,3-*seco*-aromadendranes (181–223), isozieranes (226, 228, 229), barbatanes (= gymnomitrane) (234–259), bazzananes (260–271), brasilanes (341–345), trinorcalamenanes (418), chiloscypphanes (444–450, 453, 454), cuparane dimers (491), *seco*-cuparanes (498), herbertanes (508–527) and herbertane dimers (528–531), peculiaranes (550), isogermacrane (693, 694), bicyclohumulanes (776), striatanes (808–810), tridensanes (811), ricciocarpanes (811a, 811b), myltaylanes (814–818), cyclomyltaylanes (819–830), modified pacifigorgianes (833–839), pinguisanes (840–853, 857–890), pinguisane dimers (854–856), trifaranes (906–912), neotrifaranes (913), chenopodanes (917, 918), sandvicane (919), riccardiphane (924–924b), olivacane (927), and nudenane (928, 929). Africanes (84–102), aristrane (108–120), zierane (224, 225, 227), azulene (230–232), bergamotane (272–281), brasilanes (341–345), nardosinane (831, 832), santalane (891–897), and thujopsane (901–905) are also found among a restricted number of liverworts and are relatively rare groups of naturally occurring sesquiterpenoids.

Compounds of the spiroclerodane (956–959, 965, 966), 5,10-*seco*-clerodane (996, 997), 9,10-*seco*-clerodane (1008, 1011–1014), verrucosane (1055–1067), *epi*-homoverrucosane (1071–1077), fusicoccane-labdane dimer (1120–1122), fusicoccane-aromadendrane dimer (1123), fusicoccane-bibenzyl dimers (1124, 1125), secoinfuscane (1238), infuscane (1239), *abeo*-labdane (1295–1307), sacculatane (1348–1375), sphenolobane (1376–1387), and hatcherane types

(1420) are representative of diterpenoids found only among liverworts. In turn, cyatanes (1068–1070), dolabellanes (1078–1094), fusicocanes (1095–1119), cembranes (945–955a), vibsanes (1404–1408), neodenudatanes (1409, 1410), prenylguaianes (1415), an *abeo*-abietane (1417), and viscidanes (1411, 1412) are rare naturally occurring diterpenoids found among the liverworts.

Various types of bis-bibenzyls (1558–1659) are the most characteristic compounds isolated from the liverworts. These compounds occur in the Marchantiaceae and Aytoniaceae of the Marchantiales, and the Lejeuneaceae, Lepidoziaceae, and Plagiochilaceae of the Jungermanniales, and the Blasiaceae, Pelliaceae and Riccardiaceae of the Metzgeriales, although in some rare cases the same compounds have been found in a fern (633), and a higher plant (439). Naturally rare bibenzyl cannabinoids (1545, 1546) and bibenzyls (1511–1513, 1516–1518) with a dihydrooxepin, and related bibenzyls possessing a cyclopropane ring (1514, 1515, 1519, 1520) have been found only in the liverwort genus, *Radula*, belonging to the Jungermanniales.

In contrast, the occurrence of nitrogen- and sulfur-containing compounds among the bryophytes is very rare. Examples include skatole (1878) in a unidentified Malaysian liverwort, a *Mannia* or *Asterella* species (71) and *Cyathodium foetidissimum* (494) and two prenyl indole derivatives (2199, 2200) from *Riccardia camedlyfolia*, and the benzyl and β -phenethyl β -methylthioacrylates, isotachin A (1880) and isotachin B (1881) from the liverworts, *Isotachis* and *Balantiopsis* species (40, 73, 288, 457). Moreover, several nitrogen-containing compounds, the coriandrins (1882, 1883) and the methyl tridentatols (1884, 1885) have been isolated from the Mediterranean liverwort, *Corsinia coriandrina* belonging to the Corsiniaceae (Marchantiales) (79, 921).

Flavonoids are extremely common constituents of the bryophytes and have been isolated from or detected in both the Marchantiophyta and the Bryophyta (40). Almost all liverworts elaborate stigmaterol (1421) and squalene (1432) as well as α -tocopherol (1876) (82). Highly unsaturated fatty acids and alkanones, such as eicosapentaenoic acid (EPA (20:5n-3)) (2026), 10,13,16,19-docosatetraenoic acid (22:4n-3) (2030) and triterpenoids, like the hopanoids (40), are characteristic components of the Bryophyta. Some neolignans (2169b, 2169c) serve as important chemical markers for the Anthocerotophyta (40).

The presence of terpenoid glycosides is very rare in the Marchantiophyta. A few bitter-tasting *ent*-kaurene glycosides have been found in the *Jungermannia* species (40). In addition, a number of flavonoid glycosides have been detected both in the liverworts and the mosses.

3.2 Chirality of Terpenoids from the Marchantiophyta

A characteristic structural phenomenon of liverwort constituents is that most sesqui- and diterpenoids are enantiomers of those found in higher plants, although there are a few exceptions such as compounds in the drimane, germacrane, and

guaiane classes. In the case of monoterpenoids, the presence of some enantiomers, like (+)-bornyl acetate (**58**) and its derivatives, of those found in higher plants have been detected in the Marchantiophyta (**40**, **880**).

The (–)-enantiomer of bicyclogermacrene (**293**) was isolated from the liverwort *Jamesoniella autumnalis*, while the (+)-enantiomer was obtained from *Majorana hortensis* oil. (–)-Calarene (**109**) is a sesquiterpene hydrocarbon found in *Scapania aequiloba*, with its (+)-isomer being commercially available. (–)- α - (**575**) and (+)- β -Selinene (**577**) were found in the liverworts *Lophocolea bidentata* and *Pedinophyllum interruptum*, respectively. *Reboulia hemisphaerica* produces (+)-thujopsene (**901**), while the (–)-enantiomer is a major component of cedar wood oil. *Conocephalum conicum* also produces the unusual enantiomers, (+)- α - (**234**) and (+)- β -barbatene (**235**) as well as (+)- β -elemene (**283**), while their enantiomers have been obtained from *Piper cubeba* (**432**).

It is noteworthy that different species of the same genera, like *Frullania tamarisci* and *F. dilatata* (Frullaniaceae), may each produce different sesquiterpene enantiomers. For example, (–)-frullanolide (**658**) has been found in *F. tamarisci* subsp. *tamarisci* (**39**, **40**) and *F. nisqualensis* (**410**), while *Frullania dilatata* (**578**), *F. brasiliensis* (**98**) and *F. muscicola* (**443**) biosynthesize (+)-frullanolide (**659**).

Some liverworts, such as *Lepidozia* (Lepidoziaceae) or *Chiloscyphus* (Lophocoleaceae) species, may biosynthesize both enantiomers of a given compound. One example is given by a mixture of enantiomeric isomers of eudesm-4(15)-en-7 α -ol (**605**) in *Lepidozia vitrea* and *Chiloscyphus polyanthos* (**890**). Another example of the presence of both enantiomers of a compound occurring in the same liverwort is *Jungermannia infusca* collected in two locations in Japan. A specimen obtained in Kochi produced optically pure (+)-kolavelool (**968**), while the sample procured in Tokushima contained pure (–)-kolavelool (**967**) as the main component (**600**).

3.3 Essential Oils of Some Marchantiophyta Species

The contents of the oil bodies of the Marchantiophyta are easily extracted with solvent using ultrasonic apparatus and by steam or hydrodistillation. Generally, the chemical constituents of the essential oils of liverworts are very complex.

The essential oil of the Taiwanese *Lepidozia fauriana* was analyzed by GC/MS to detect viridiflorol (**127**), isodene (**130**), (–)-isospathulenol (**137**), (**531**), globulol (**139**), aromadendrene (**156**), *allo*-aromadendrene (**158**), β -barbatene (**234**), β -bazzanene (**261**), δ -elemene (**282**), β -elemene (**283**), and (–)-bicyclogermacrene (**293**) (**40**), (–)-lepidozenal (**308**) (**40**), α -amorphene (**367**), β -caryophyllene (**426**), β -cedrene (**432**), β -cedrol (**433**), (+)-dihydrochiloscypholone (**446**) (**583**), (+)-11,12-dihydrochiloscypholone (**453**), (+)-7,10-anhydro-11,12-dihydrochiloscypholone (**454**), α -copaene (**455**), α -ylangene (**457**), δ -cuprenene (**468**), eudesm-4-en-7 α -ol (**606**) (**103**), longifolene (**778**), isosativene (**792**), maaliol (**798**), and thujopsene (**901**).

From the essential oil of the Taiwanese *Lepidozia vitrea*, ledene (**129**), spathulenol (**136**), vetivazulene (**233**) (**39**), α -barbatene (**234**), β -barbatene (**235**),

isobazzanene (260), δ -elemene (282), β -elemene (283), (+)-elema-1,3-dien-7 β -ol (288), (+)-7 β -acetoxyelema-1,3-dien-8 β -ol (289), β -bourbonene (336), δ -cadinene (347), α -ylangene (457), cuparene (464), α -cuprenene (464), δ -selinene (532), rosifoliol (593), (+)-eudesm-3-en-7 α -ol (603) (890), eudesm-4(15)-en-7 α -ol (605) (890), (–)-eudesm-4-en-7 α -ol (606), 5-guaien-11-ol (736), germacrene B (690), γ -maaliene (725), and maaliol (798) were obtained.

The essential oil of the European *Plagiochila asplenioides* was also analyzed by GC/MS, to identify β -acoradiene (68), anastreptene (122), α - (234) and β -barbatene (235), β -bazzanene (261), (–)-bicyclogermacrene (293), γ -curcumene (335), β -chamigrene (436), α -cuprenene (466), α -chamigrene (435), (+)- δ -selinene (578), α -maaliene (794), γ -maaliene (796), italicene (922), β -funebrene (923) (14), as sesquiterpene hydrocarbons, and plagiochilide (203), gymnomitr-3(15)-en-4 β -ol (244), 3 α -acetoxybicyclogermacrene (298), rosifoliol (593), and (+)-maalian-5-ol (800), as oxygenated sesquiterpenoids (14).

3.4 Chemical Constituents of *in vitro* Cultured Cells and Field Gametophytes of Some Marchantiophyta Species

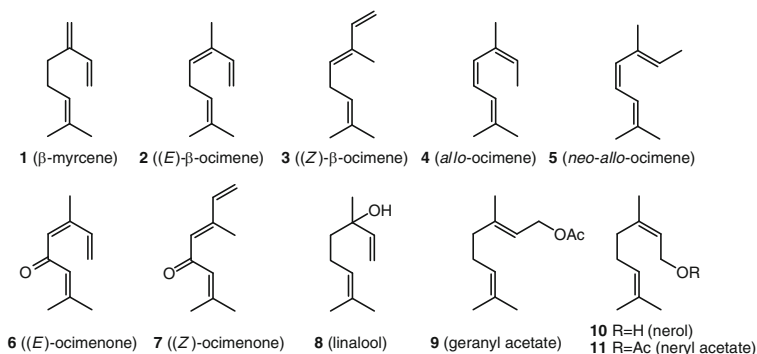
Comparative studies of the secondary metabolites of the field gametophytes and *in vitro* cultured cells of the same liverwort species are important, in order to understand whether different components from each procedure are obtained. The distribution of sesquiterpenoids in field-collected and *in vitro*-cultured *Jamesoniella autumnalis* was investigated (109). Anastreptene (122), spathulenol (136), β -barbatene (235), bicyclogermacrene (293), 3 α -acetoxybicyclogermacrene (298), α -bisabolene (313), and β -bisabolene (315) were identified in both types of samples. It was found that the sesquiterpene pattern of *J. autumnalis* from its natural habitat had almost the same sesquiterpenoid composition as its *in vitro* cultures qualitatively and quantitatively.

Three clerodane 20-carboxylic acids, heteroscyphic acids A (961), B (962), and C (963), were isolated from the calli and cells from suspension cultures of *Heteroscyphus planus*. The same carboxylic acids are present also in field-collected *H. planus*. However, their amounts in the acidic fractions of the suspension cells are 4–13 times lower than those in the native plant material (561). These diterpenoid acids might be precursors of spiroclerodane-type diterpenoids, e.g. heteroscyphones A-D (956–959), isolated from field-collected *H. planus* (310).

4 Chemical Constituents of Marchantiophyta

4.1 Monoterpenoids

Jungermannia hattoriana produces β -cyclocitral (**12**) (see Table 4.1). This represented the first isolation of this compound among the liverworts, when initially reported (590), although α -terpineol (**17**) has been isolated from *Jungermannia vulcanicola* (40).



Acyclic monoterpeneoids found in the Marchantiophyta

Figueiredo and associates analyzed the essential oils of four Madeiran *Plagiochila* species, *P. bifaria*, *P. maderensis*, *P. retrorsa*, and *P. stricta* by GC and GC/MS (221). Seventeen monoterpeneoids were detected in *P. bifaria*, but, their overall percentage content was relatively low (0.1–5.0%). Among these, terpinolene (**15**) and β -phellandrene (**27**) were predominant. On the other hand, *P. maderensis*, *R. retrorsa*, and *P. stricta* are rich sources of monoterpeneoids. *P. maderensis* contained terpinolene (**15**) (33.5–60.0%), while *P. retrorsa* produced *allo*-ocimene (**4**) (4.9–15.0%), *neo-allo*-ocimene (**5**) (4.2–9.6%), β -phellandrene (**27**) (5.5–46.9%), and terpinolene (**15**) (12.9%). In the case of *P. stricta*, the major monoterpeneoids were *allo*-ocimene (**4**) (6,7–19.1%) and *neo-allo*-ocimene (**5**) (3.7–10.5%) (221).

Table 4.1 Monoterpenoids found in the Marchantiophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1	β -Myrcene	C ₁₀ H ₁₆			<i>Asterella africana</i>	(222)	
					<i>Asterella venosa</i>	(492)	
					<i>Conocephalum conicum</i>	(492)	
					<i>Frullania falciloba</i>	(78)	
					<i>Plagiochila bifaria</i>	(221)	
2	(E)- β -Ocimene	C ₁₀ H ₁₆			<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Asterella africana</i>	(222)	
					<i>Plagiochila bifaria</i>	(221)	
3	(Z)- β -Ocimene	C ₁₀ H ₁₆			<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
4	<i>allo</i> -Ocimene	C ₁₀ H ₁₆			<i>Plagiochila stricta</i>	(221)	
					<i>Radula perrottetii</i>	(826)	
					<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
5	<i>neo-allo</i> -Ocimene	C ₁₀ H ₁₆				(699)	
					<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
6	(E)-Ocimenone	C ₁₀ H ₁₄ O			<i>Plagiochila stricta</i>	(221)	
						(699)	
					<i>Trichocolea pluma</i>	(494)	
7	(Z)-Ocimenone	C ₁₀ H ₁₄ O			<i>Trichocolea pluma</i>	(494)	
8	Linalool	C ₁₀ H ₁₈ O			<i>Asterella africana</i>	(222)	
					<i>Chandonanthus hirtellus</i>	(423)	
						(494)	

9	Geranyl acetate	$C_{12}H_{20}O_2$	<i>Plagiochila bifaria</i>	(221)
			<i>Radula carringtonii</i>	(223)
			<i>Trichocolea pluma</i>	(494)
			<i>Asterella venosa</i>	(492)
			<i>Plagiochila retrorsa</i>	(221)
			<i>Plagiochila stricta</i>	(221)
			<i>Wiesnerella denudata</i>	(492)
			<i>Conocephalum conicum</i>	(492)
			<i>Wiesnerella denudata</i>	(492)
			<i>Jungermannia hattoriana</i>	(590)
10 11	Nerol Neryl acetate	$C_{10}H_{18}O$ $C_{12}H_{20}O_2$	<i>Plagiochila bifaria</i>	(221)
			<i>Plagiochila fasciculata</i>	(72)
			<i>Plagiochila maderensis</i>	(221)
			<i>Plagiochila retrorsa</i>	(221)
				(698)
			<i>Plagiochila rutilans</i>	(693)
			<i>Plagiochila standleyi</i>	(693)
			<i>Plagiochila stephensoniana</i>	(72)
			<i>Plagiochila stricta</i>	(221)
			<i>Radula boryana</i>	(224)
14	γ -Terpinene	$C_{10}H_{16}$	<i>Radula perrottetii</i>	(826)
			<i>Asterella africana</i>	(222)
			<i>Bazzania japonica</i>	(485)
			<i>Plagiochila bifaria</i>	(221)
			<i>Plagiochila maderensis</i>	(221)
			<i>Plagiochila retrorsa</i>	(221)
			<i>Plagiochila stricta</i>	(221)
			<i>Radula boryana</i>	(224)
			<i>Radula perrottetii</i>	(826)
			<i>Asterella africana</i>	(222)
15	Terpinolene	$C_{10}H_{16}$	<i>Bryopteris filicina</i>	(604)

(continued)

Table 4.1 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
					<i>Drepanolejeunea madagascariensis</i>	(247)	
					<i>Plagiochila bifaria</i>	(221)	
					<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila rutilans</i>	(693)	
					<i>Plagiochila stricta</i>	(221)	
						(699)	
					<i>Radula boryana</i>	(224)	
					<i>Radula perrottetii</i>	(826)	
					<i>Asterella africana</i>	(222)	
					<i>Plagiochila bifaria</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Asterella africana</i>	(222)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Asterella africana</i>	(222)	
					<i>Asterella africana</i>	(222)	
					<i>Barbilophozia floerkei</i>	(15)	
					<i>Bazzania harpago</i>	(490)	
					<i>Bazzania praerupta</i>	(880)	
					<i>Conocephalum conicum</i>	(492)	
						(493)	
					<i>Conocephalum japonicum</i>	(224)	
					<i>Chandonanthus hirtellus</i>	(247)	
						(490)	
					<i>Drepanolejeunea madagascariensis</i>	(490)	
16	Terpinen-4-ol	C ₁₀ H ₁₈ O					
17	α-Terpineol	C ₁₀ H ₁₈ O					
18	α-Terpinyl acetate	C ₁₂ H ₂₀ O ₂					
19	Limonene	C ₁₀ H ₁₆					

20	Isopiperitenone		<i>Dumortiera hirsuta</i>	(323)
21	<i>p</i> -Cymene	C ₁₀ H ₁₄ O C ₁₀ H ₁₄	<i>Herbertus sakuraii</i> <i>Kurzia makinoana</i> <i>Marsipella emarginata</i> <i>Marchesinia mackaii</i> <i>Marchantia paleacea</i> var. <i>diptera</i> <i>Plagiochila bifaria</i> <i>Plagiochila maderensis</i> <i>Plagiochila retrorsa</i> <i>Plagiochila rutilans</i> <i>Plagiochila stricta</i> <i>Radula boryana</i> <i>Radula complanata</i> <i>Wiesnerella denudata</i> <i>Trichocolea pluma</i> <i>Asterella africana</i> <i>Plagiochila bifaria</i> <i>Plagiochila maderensis</i> <i>Plagiochila retrorsa</i>	(882) (17) (220) (877) (492) (221) (221) (693) (221) (224) (223) (490) (492) (494) (222) (221) (221) (221) (698) (693) (693) (221) (224) (826) (221) (221) (693) (221) (221)
22	<i>p</i> -Cymen-8-ol	C ₁₀ H ₁₄ O	<i>Plagiochila rutilans</i> <i>Plagiochila standleyi</i> <i>Plagiochila stricta</i> <i>Radula boryana</i> <i>Radula perrottetii</i> <i>Plagiochila maderensis</i> <i>Plagiochila retrorsa</i> <i>Plagiochila rutilans</i> <i>Plagiochila stricta</i> <i>Radula boryana</i>	(693) (693) (221) (224) (826) (221) (221) (693) (221) (221) (224)
				(continued)

Table 4.1 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ /° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
23	<i>m</i> -Cymen-8-ol	C ₁₀ H ₁₄ O			<i>Plagiochila stricta</i>	(221)	
24	Carvacrol	C ₁₀ H ₁₄ O			<i>Marchantia berteroa</i>	(72)	
					<i>Plagiochila fasciculata</i>	(72)	
					<i>Radula boryana</i>	(224)	
25	Thymol	C ₁₀ H ₁₄ O			<i>Trichoclea lanata</i>	(72)	
					<i>Marchantia berteroa</i>	(72)	
					<i>Plagiochila fasciculata</i>	(72)	
					<i>Radula boryana</i>	(224)	
26	α -Phellandrene	C ₁₀ H ₁₆			<i>Trichoclea lanata</i>	(72)	
					<i>Drepanolejeunea</i>	(247)	
					<i>madagascariensis</i>		
					<i>Plagiochila bifaria</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Radula holtii</i>	(223)	
27	β -Phellandrene	C ₁₀ H ₁₆			<i>Asterella africana</i>	(222)	
					<i>Drepanolejeunea</i>	(247)	
					<i>madagascariensis</i>		
					<i>Plagiochila bifaria</i>	(221)	
						(333)	
					<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
						(698)	
					<i>Plagiochila rutilans</i>	(693)	
					<i>Plagiochila standleyi</i>	(693)	
					<i>Plagiochila stricta</i>	(221)	
28	Pulegone	C ₁₀ H ₁₆ O			<i>Plagiochila rutilans</i>	(693)	
29	3,7-Dimethyl-2,6-octadien-1,6-olide	C ₁₀ H ₁₄ O ₂			<i>Plagiochila rutilans</i>	(693)	

30	1,3,8-Menthatriene	C ₁₀ H ₁₄	<i>Plagiochila maderensis</i>	(221)
31	Menthone	C ₁₀ H ₁₈ O	<i>Plagiochila rutilans</i>	(693)
32	Isomenthone	C ₁₀ H ₁₈ O	<i>Asterella africana</i>	(222)
33	<i>trans</i> - <i>p</i> -Menth-2-en-1-ol	C ₁₀ H ₁₈ O	<i>Plagiochila rutilans</i>	(693)
			<i>Plagiochila bifaria</i>	(221)
34	<i>cis</i> - <i>p</i> -Menth-2-en-1-ol	C ₁₀ H ₁₈ O	<i>Plagiochila retrorsa</i>	(221)
35	<i>p</i> -Menth-1-en-9-ol	C ₁₀ H ₁₈ O	<i>Plagiochila retrorsa</i>	(221)
			<i>Drepanolejeunea</i>	(247)
			<i>madagascariensis</i>	
36	<i>p</i> -Menth-1-en-9-yl acetate	C ₁₂ H ₂₀ O ₂	<i>Drepanolejeunea</i>	(247)
			<i>madagascariensis</i>	
37	<i>p</i> -Menth-1,8(9)-dien-10-ol	C ₁₀ H ₁₆ O	<i>Drepanolejeunea</i>	(247)
			<i>madagascariensis</i>	
38	Dill ether (= 3,9-Epoxy- <i>p</i> -menth-1-ene)	C ₁₀ H ₁₆ O	<i>Drepanolejeunea</i>	(247)
			<i>madagascariensis</i>	
39	Ascaridole	C ₁₀ H ₁₆ O ₂	<i>Plagiochila standleyi</i>	(693)
40	Δ ³ -Carene	C ₁₀ H ₁₆	<i>Radula perrottetii</i>	(826)
			<i>Wiesnerella denudata</i>	(492)
41	Δ ² -Carene	C ₁₀ H ₁₆	<i>Bryopteris filicina</i>	(604)
42	1,8-Cineole	C ₁₀ H ₁₈ O	<i>Asterella africana</i>	(222)
			<i>Chandonanthus hirtellus</i>	(224)
43	α-Thujene	C ₁₀ H ₁₆	<i>Asterella africana</i>	(222)
			<i>Plagiochila maderensis</i>	(221)
			<i>Plagiochila retrorsa</i>	(221)
			<i>Plagiochila stricta</i>	(221)
44	Sabinene	C ₁₀ H ₁₆	<i>Asterella africana</i>	(222)
			<i>Asterella echinella</i>	(492)
			<i>Conocephalum conicum</i>	(492)
			<i>Jungmannia truncata</i>	(601)
			<i>Plagiochila bifaria</i>	(221)

(continued)

Table 4.1 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D/\text{°cm}^2\text{g}^{-1}10^{-1}$	Plant source(s)	Reference(s)	Comments
45	(–)-Sabinene	C ₁₀ H ₁₆ C ₁₀ H ₁₈ O			<i>Plagiochila rutilans</i>	(693)	
					<i>Plagiochila stricta</i>	(221)	
	<i>cis</i> -Sabinene hydrate	<i>Conocephalum conicum</i>			(880)		
		<i>Plagiochila bifaria</i>			(221)		
46	<i>trans</i> -Sabinene hydrate	C ₁₀ H ₁₈ O			<i>Plagiochila stricta</i>	(221)	
					<i>Asterella africana</i>	(222)	
					<i>Plagiochila bifaria</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
47	α -Pinene	C ₁₀ H ₁₆			<i>Asterella africana</i>	(222)	
					<i>Asterella venosa</i>	(492)	
					<i>Barbilophozia floerkei</i>	(15)	
					<i>Bazzania japonica</i>	(485)	
					<i>Corsinia coriandrina</i>	(79)	
						(921)	
					<i>Dendromastigophora flagellifera</i>	(72)	
					<i>Frullania falciloba</i>	(78)	
					<i>Frullania pycnantha</i>	(78)	
					<i>Frullania spinifera</i>	(78)	
					<i>Jungermannia truncata</i>	(601)	
					<i>Lophozia ventricosa</i>	(486)	
					<i>Lunularia cruciata</i>	(79)	
					<i>Marsupella alpina</i>	(17)	
					<i>Marsupella emarginata</i>	(17)	
					<i>Marchantia paleacea</i> var. <i>diptera</i>	(877)	
						<i>Plagiochila bifaria</i>	(221)
	<i>Plagiochila maderensis</i>	(221)					

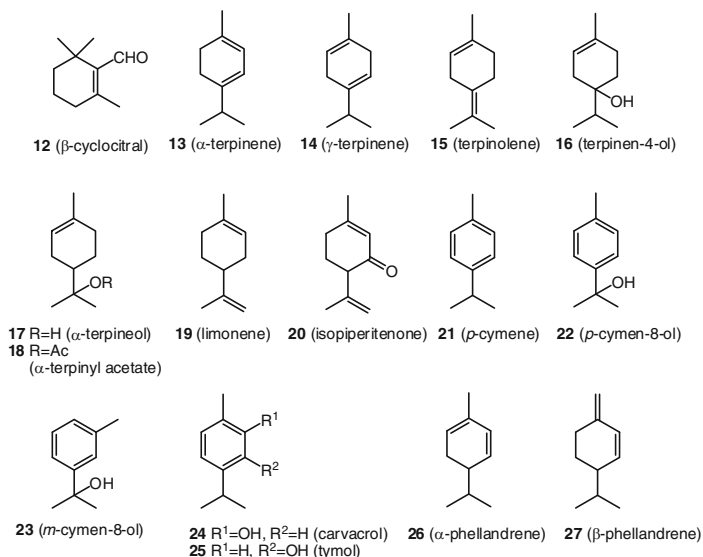
48	β -Pinene	$C_{10}H_{16}$	<i>Plagiochila retrorsa</i>	(221)
			<i>Plagiochila stricta</i>	(221)
			<i>Radula aquilegia</i>	(223)
			<i>Radula boryana</i>	(224)
			<i>Radula complanata</i>	(223)
			<i>Radula holtii</i>	(223)
			<i>Radula lindenbergiana</i>	(223)
			<i>Radula nudicaulis</i>	(223)
			<i>Radula wichurae</i>	(223)
			<i>Saccogyna viticulosa</i>	(276)
			<i>Trichocolea pluma</i>	(494)
			<i>Asterella africana</i>	(222)
			<i>Barbilophozia floerkei</i>	(15)
			<i>Conocephalum conicum</i>	(492)
			<i>Drepanolejeunea</i>	(247)
			<i>madagascariensis</i>	
			<i>Frullania pycnantha</i>	(78)
			<i>Frullania spinifera</i>	(78)
			<i>Marchantia paleacea</i>	(492)
			var. <i>diptera</i>	
			<i>Marsupella emarginata</i>	(17)
			<i>Plagiochila rutilans</i>	(693)
			<i>Asterella africana</i>	(222)
			<i>Asterella africana</i>	(222)
			<i>Asterella africana</i>	(222)
			<i>Asterella africana</i>	(222)
			<i>Asterella venosa</i>	(492)
			<i>Saccogyna viticulosa</i>	(276)
			<i>Plagiochila retrorsa</i>	(221)
			<i>Asterella africana</i>	(222)
			<i>Asterella africana</i>	(222)
49	<i>trans</i> -Pinocarveol	$C_{10}H_{16}O$		
50	Myrtenal	$C_{10}H_{14}O$		
51	Myrtenol	$C_{10}H_{16}O$		
52	Myrtenyl acetate	$C_{12}H_{18}O_2$		
53	<i>cis</i> -Verbenyl acetate	$C_{12}H_{18}O_2$		
54	Fenchyl acetate	$C_{12}H_{20}O_2$		
55	Camphene	$C_{10}H_{16}$		

(continued)

Table 4.1 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ ° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
56	Tricyclene	C ₁₀ H ₁₆			<i>Barbilophozia floerkei</i>	(15)	
					<i>Conocephalum conicum</i>	(492)	
					<i>Marsupella emarginata</i>	(17)	
					<i>Saccogyna viticulosa</i>	(276)	
					<i>Asterella africana</i>	(222)	
57	Borneol	C ₁₀ H ₁₈ O			<i>Marsupella emarginata</i>	(17)	
					<i>Saccogyna viticulosa</i>	(276)	
					<i>Trichocolea pluma</i>	(494)	
					<i>Asterella africana</i>	(222)	
					<i>Wiesnerella denudata</i>	(490)	
58	Bornyl acetate	C ₁₂ H ₂₀ O ₂			<i>Asterella africana</i>	(222)	
					<i>Wiesnerella denudata</i>	(490)	
59	(+)-Bornyl acetate	C ₁₂ H ₂₀ O ₂			<i>Conocephalum conicum</i>	(880)	
60	(+)-Bornyl <i>p</i> -coumarate	C ₁₉ H ₂₄ O ₃		+15.6	<i>Conocephalum conicum</i>	(880)	
61	(+)-Bornyl ferulate	C ₂₀ H ₂₆ O ₄			<i>Conocephalum conicum</i>	(880)	
61	(+)-Bornyl <i>cis</i> -4-hydroxycinnamate	C ₁₉ H ₂₄ O ₃			<i>Conocephalum conicum</i>	(880)	
62	(+)-Bornyl <i>cis</i> -4-hydroxy-3-methoxycinnamate	C ₂₀ H ₂₆ O ₃		+18.2	<i>Conocephalum conicum</i>	(880)	
63	2 α -Cinnamoyloxy-6 β -acetoxybornane	C ₂₁ H ₂₆ O ₄		+18.3	<i>Conocephalum conicum</i>	(295)	
64	2 α ,5 β -Dihydroxybornane-2-cinnamate	C ₁₉ H ₂₄ O ₃			<i>Conocephalum conicum</i>	(487)	
65	2 α ,5 β -Dihydroxybornane-5-acetoxy-2-cinnamate	C ₂₁ H ₂₆ O ₄			<i>Conocephalum conicum</i>	(487)	
66	2 α ,5 β -Dihydroxybornane-2- <i>p</i> -hydroxycinnamate	C ₁₉ H ₂₄ O ₄			<i>Conocephalum conicum</i>	(487)	
67	2 α ,5 β -Dihydroxybornane-2-(<i>Z</i>)- <i>p</i> -hydroxycinnamate	C ₁₉ H ₂₄ O ₃			<i>Conocephalum conicum</i>	(487)	

Application of the HS-SPME (head space-solid phase micro-extraction) technique coupled with GC/MS analysis led to the detection of volatile components of *Drepanolejeunea madagascariensis*, which shows a pleasant, sweet, warm, woody-spicy, and herbaceous fragrance. Among 34 compounds identified, limonene (**19**), *p*-menth-1-en-9-ol (**35**), β -phellandrene (**27**), and dill ether (**38**) were found to be the major volatile components. In addition, β -myrcene (**1**), α -terpinene (**13**), terpinolene (**15**), terpinen-4-ol (**16**), α -terpineol (**17**), limonene (**19**), *p*-cymene (**21**), α -phellandrene (**26**), *p*-mentha-1,8(9)-dien-10-ol (**37**), *p*-menth-1-en-9-yl acetate (**36**), α -pinene (**47**), and β -pinene (**48**) were detected as minor constituents (**247**).



Monocyclic monoterpenoids found in the Marchantiophyta

It is known that there are three chemotypes of *Conocephalum conicum* (Fig. 4.1), with one producing (–)-sabinene (**44**) (Type I), the second elaborating (+)-bornyl acetate (**58**) (Type II), and the third being very characteristic since it biosynthesizes (*E*)-methyl cinnamate (**1836**) (Type III) (**40**, **492**, **856**). *Conocephalum conicum* produces not only (+)-bornyl acetate (**58**) but also related esters, *e.g.* bornyl ferulate (**60**) (**39**).

Further investigation of the ether extract of *C. conicum* (Types I, II, and II) resulted in the isolation of three new monoterpene esters, namely, (+)-bornyl *p*-coumarate (**59**) from type I with (+)-bornyl ferulate (**60**), and bornyl *cis*-4-hydroxycinnamate (**61**) from type II, and bornyl *cis*-4-hydroxy-3-methoxycinnamate (**62**) from types II and III. The structures of **59**, **61**, and **62** were established readily from their ¹H NMR spectra and by chemical reaction. Methylation of **59** gave a monomethyl ether, which was hydrolyzed to afford *p*-coumaric acid methyl ether and (+)-bornyl acetate (**58**), indicating that the structure of **59** is (+)-bornyl *p*-coumarate. Compound **61** is the *cis*-isomer of **59** and compound **62** the stereoisomer of **60** (**880**).

A combination of Sephadex and silica gel column chromatography (CC) of the ether extract of *Conocephalum conicum* led to the isolation of 2 α -cinnamoyloxy-



Fig. 4.1 *Conocephalum conicum* (Chemotype III)

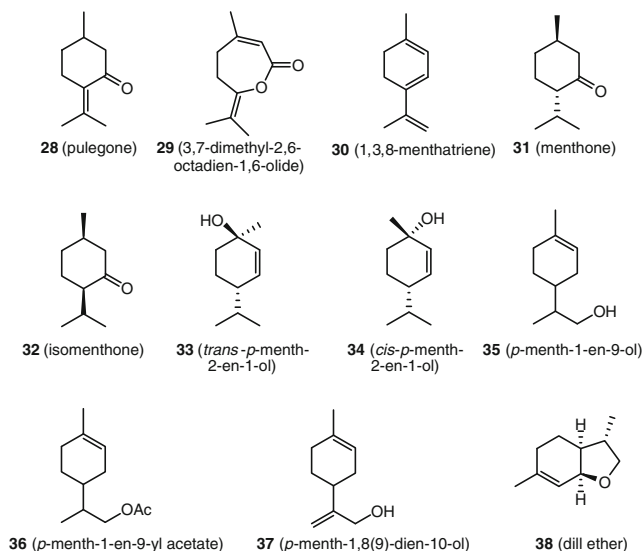
6 β -acetoxybornane (**63**), for which the stereochemistry was established using its HSQC, COSY, HMBC, and NOESY NMR spectra (**295**).

The Chinese *C. conicum* also elaborates four bornyl esters, namely, 2 α ,5 β -dihydroxybornane-2-cinnamate (**64**), 2 α ,5 β -dihydroxybornane-5-acetyl-2-cinnamate (**65**), 2 α ,5 β -dihydroxybornane-2-*p*-hydroxycinnamate (= coumarate) (**66**), and 2 α ,5 β -dihydroxy-2-*cis-p*-hydroxycinnamate (**67**) (**487**).

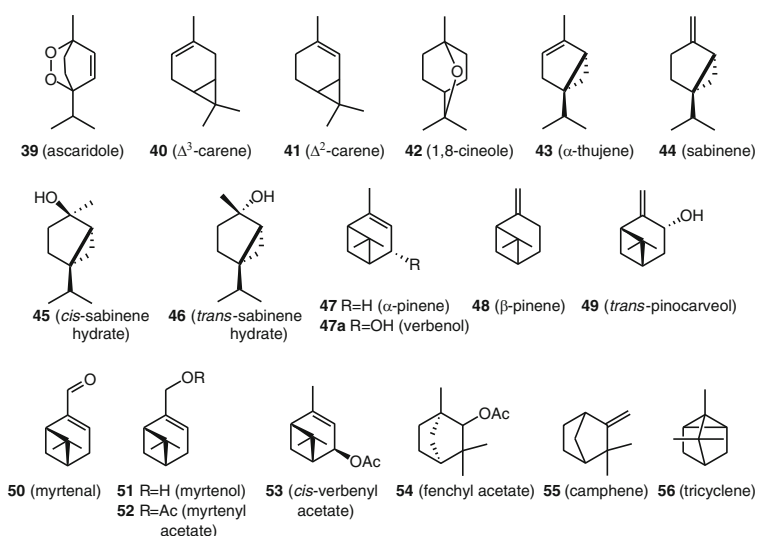
(–)-Sabinene (**44**) and (+)-bornyl acetate (**58**) are the major monoterpenes produced by a Japanese and European strain, and a Japanese and a North American strain, respectively, of *Conocephalum conicum*. The biosynthesis of both compounds **44** and **58** has been investigated, in which the cyclization of geranyl diphosphate was catalyzed by the partially purified sabinene synthase from *C. conicum*. It was demonstrated that bornane-type monoterpenoids are derived from geranyl diphosphate in *C. conicum*, as in higher plants, by action of bornyl diphosphate synthase (**9**). Thiel and Adam studied the biosynthesis of bornyl acetate (**58**) from the same species using [1-¹³C]1-deoxy-D-xylose and suggested that bornyl acetate biosynthesis takes place in the oil cells of *C. conicum* (**831**).

The CDCl₃ extracts of the Bolivian, Brazilian, and Costa Rican samples of *Plagiochila lutilans*, a species exhibiting a peppermint-like odor, was investigated by GC and GC/MS to detect a variety of monoterpenoids, including α -terpinene (**13**), terpinolene (**15**), limonene (**19**), *p*-cymene (**21**), β -phellandrene (**27**), *p*-cymen-8-ol (**22**), pulegone (**28**), 3,7-dimethyl-2,6-octadien-1,6-olide (**29**), menthone (**31**), isomenthone (**32**), sabinene (**44**), and β -pinene (**48**), among which pulegone (**28**) was the major component. Additional abundant components were terpinolene (**15**), limonene (**19**), and *p*-cymen-8-ol (**22**). One of the Costa Rican specimens produced 3,7-dimethyl-2,6-octadien-1,6-olide (**29**) as the principal component. GC and GC/MS of the CDCl₃ extract of *Plagiochila standleyi*, also possessing a peppermint odor, showed the presence of α -terpinene (**13**), limonene

(19), *p*-cymene (21), β -phellandrene (27), and ascaridole (39), of which limonene (19) and ascaridole (39) were the most abundant. Older specimens of *P. rutilans* from Cuba and Ecuador were also analyzed by GC and GC/MS, which indicated that the major components of the former specimen were menthone (31) and *p*-cymen-8-ol (22), and for the latter specimen, pulegone (28) was obtained (693). *Plagiochila killarniensis*, *P. spinulosa*, and *P. punctata* also emit strong “aromatic” smells when fresh materials are crushed. This may be attributed to β -phellandrene (27), which was found to be present in all three species (696).



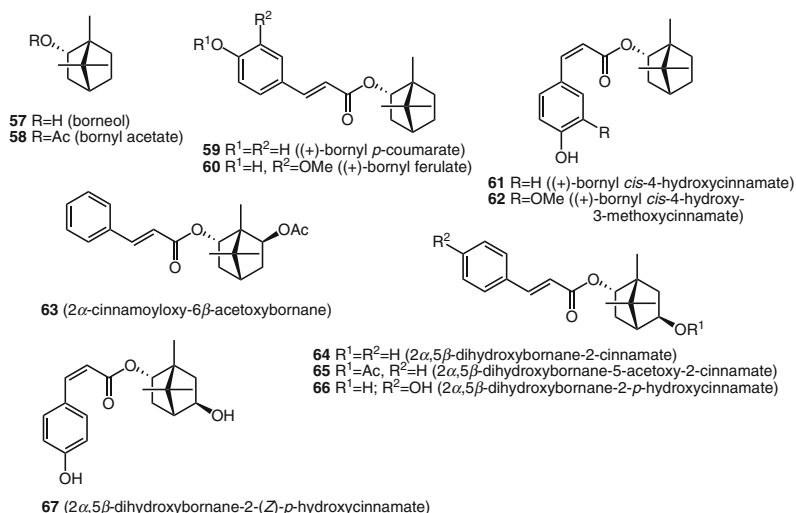
Mono- and bicyclic monoterpenoids found in the Marchantiophyta



Di- and tricyclic monoterpenoids found in the Marchantiophyta

Some *Asterella* species belonging to the Marchantiales emit characteristic unpleasant or uncomfortable odors. The essential oils of the western European *A. africana* collected in both Madeira and mainland Portugal were analyzed by GC and GC/MS. α -Pinene (**47**) (13–17%) and myrtenyl acetate (**52**) (38–42%) were identified as the major components in both samples. The Madeira sample contained sabinene (**44**) and myrtenal (**50**) in 6–8% yields, however, these components were detected only in trace amounts from the mainland specimen (**222**).

The ether extract of two Mexican *Asterella* species, *A. venosa* and *A. echinella*, elaborated, in turn, geranyl acetate (**9**) and sabinene (**44**) as the main component. The latter species also contained β -myrcene (**1**), α -pinene (**47**), and myrtenyl acetate (**52**) (**492**).



Borneol and its cinnamate derivatives found in the Marchantiophyta

A reinvestigation of the essential oils of *Saccogyna viticulosa* by GC and GC/MS resulted in the identification of α -pinene (**47**), myrtenyl acetate (**52**), camphene (**55**), and tricyclene (**56**) (**276**).

The volatile components of six French Polynesian liverworts were analyzed by GC/MS. *Trichocolea pluma* contained (*E*)-ocimenone (**6**) and (*Z*)-ocimenone (**7**) as predominant components and linalool (**8**), α -pinene (**47**), and sabinene (**44**), as minor components (**494**). *T. lanata* produced thymol (**25**) and carvacrol (**24**), together with trichocolein (**1747**), a methyl benzoate with a prenyl ether group (**72**).

Marchantia berteriana produced *ent*-cuparene (**464**) and 2-cuparenol (**483**). Reinvestigation of the ether extract of this species led to the identification of thymol (**25**) and carvacrol (**24**) together with two cuparenoids (**72**). Limonene (**19**) and α -pinene (**47**) were detected in *Marchantia paleacea* subsp. *diptera* (**877**). Further investigation of the essential oil of *Lophozia ventricosa* resulted in the identification of α -pinene (**47**) in trace amounts (**486**).

Reinvestigation of the chemical constituents of the essential oil of *Barbilophozia floerkei* resulted in the identification of limonene (**19**), α -pinene (**47**), β -pinene (**48**), and camphene (**55**) by GC and GC/MS as minor components (**15**).

4.2 Sesquiterpenoids

4.2.1 Acoranes

Acorane sesquiterpenoids are rare in liverworts. In several *Radula* species, α - (68) and β -acoradienes (69) were detected (223, 224, 492, 826). The distribution of β -acoradienes in liverworts is generally more widespread than that of the α -isomer, as shown in Table 4.2. Komala and associates reported the presence of α -neocallitropsene (69a) in an unidentified *Frullania* species (424). *Barbilophozia attenuata*, *B. barbata*, *B. lycopodioides*, and *Gymnocolea inflata* produce sesquiterpenoids of the acorane type (40).

Acoradiepoide (71) was isolated from *Jungermannia hattoriana* and its structure as a C-2/C-3 and C-4/C-5 diepoide was solved by a combination of COSY, TOCSY, and HMBC NMR spectroscopic data interpretation (590). *Jungermannia infusca* elaborates a number of sesqui- and diterpenoids. Fractionation of an ether extract of *J. infusca* led to the isolation of the new 2,11-acoradien-4-ol (72), for which the stereostructure was determined using a combination of 2D-NMR spectroscopic data (HMBC, HMQC, and NOESY), except for the configuration of the hydroxy group at C-4 (595). The same species produced another new acorane sesquiterpenoid, 3-hydroxy-4-acorene (76). Oxidation of 76 gave (+)-(1R,7R,10R)-4-acoren-3-one (77), for which the optical rotation showed the opposite sign to the known (–)-acorenone (77a). Thus, structure 76 was established as being (+)-(3R)-hydroxy-4-acorene (600).

The ether extracts of the German *Barbilophozia hatcheri* and the Finnish *B. barbata* were both fractionated to afford a new acorane sesquiterpene named barbiacoradienone (74), with the stereostructure established by a combination of 2D-NMR data and X-ray crystallographic analysis (593, 596).

(–)- α -Alasken-6 β -ol (82), (–)- α -alasken-8-one (83), and 7,8-dehydro- α -acoradiene (73) were isolated from the essential oil of *Calypogeia fissa*, together with α -alaskene (80) (931), which was isolated earlier from *Barbilophozia barbata* (26). The structure of 82 was deduced by comparison of its NMR data with those of 80, and from its 2D-NMR NOESY spectrum, and as a result of the preparation of 5,6-dehydro- α -alaskene (82a) by a dehydration reaction with thionyl chloride in pyridine. The structure of 83 was also based on 2D-NMR spectroscopy and the following chemical reactions. Reduction of 83 with NaBH₄ gave two alcohols, α -alasken-8 α -ol (83a) and α -alasken-8 β -ol (83b), followed by dehydration on GC to afford 7,8-dehydro- α -acoradiene (73), which was also present in this liverwort. The absolute configurations of 73, 82, 82a, 83, 83a, and 83b, were obtained by a correlation reaction with (–)- α -alaskene (80). Catalytic hydrogenation of 73, 80, and 82, gave four identical saturated acoranes with the same MS and retention times on achiral and chiral GC phases. Thus, the absolute stereochemistry of these compounds was determined as being identical (931).

69a	α -Neocallitropsene	$C_{15}H_{26}$		<i>Radula wichurae</i>	(223)	
70	Acora-2,4-diene	$C_{15}H_{24}$		<i>Reboulia hemisphaerica</i>	(929)	
71	Acoradiopoxide	$C_{15}H_{24}O_2$		<i>Tritomaria quinqueidentata</i>	(928)	
72	2,11-Acoradien-4-ol	$C_{15}H_{24}O$	-76.8 ± 0	<i>Trocholejeunea sandwicensis</i>	(539)	
73	7,8-Dehydro- α -acoradiene	$C_{15}H_{22}$		Unidentified <i>Frullania</i> sp.	(424)	
74	Barbiacoradienone	$C_{19}H_{26}O_5$	144-147	<i>Bazzania nitida</i>	(289)	
				<i>Jungermannia hattoriana</i>	(590)	
				<i>Jungermannia infusca</i>	(595)	
				<i>Calypogeia fissa</i>	(931)	
				<i>Barbilophozia barbata</i>	(596)	X-ray
				<i>Barbilophozia hatcheri</i>	(593)	
				<i>Bazzania madagassa</i>	(291)	
75	(1S*,4S*,5S*)-Acora-8(15),9-dien-(7R*)-ol	$C_{15}H_{24}O$	-165.0	<i>Jungermannia infusca</i>	(600)	
76	(+)-(3R)-Hydroxy-4-acorene	$C_{15}H_{26}O$	+12.6	<i>Bazzania tridens</i>	(951)	
77	(+)-Acorenone B	$C_{15}H_{24}O$	+12.3	<i>Bazzania tridens</i>	(951)	
78	(+)-Acoren-7 α -ol	$C_{15}H_{26}O$	+18.7	<i>Bazzania tridens</i>	(951)	
79	4-Acoren-3-one	$C_{15}H_{24}O$		<i>Calypogeia fissa</i>	(929)	
80	(-)- α -Alaskene	$C_{15}H_{24}$		<i>Calypogeia fissa</i>	(929)	
81	β -Alaskene	$C_{15}H_{24}$		<i>Calypogeia fissa</i>	(929)	
82	(-)- α -Alasken-6 β -ol	$C_{15}H_{24}O$		<i>Calypogeia fissa</i>	(929)	
83	(-)- α -Alasken-8-one	$C_{15}H_{22}O$		<i>Calypogeia fissa</i>	(929)	
84	African-2-ene	$C_{15}H_{24}$		<i>Mastigophora diclados</i>	(425)	
					(494)	
85	African-3-ene	$C_{15}H_{24}$		<i>Herbertus aduncus</i>	(323)	
86	African-2(6)-ene	$C_{15}H_{24}$		<i>Mastigophora diclados</i>	(425)	
					(494)	
87	African-3(15)-ene	$C_{15}H_{24}$		<i>Pellia epiphylla</i>	(175)	Sporophytes
					(176)	Gametophytes
88	African-1,5-diene	$C_{15}H_{22}$		<i>Frullania scandens</i>	(78)	
89	Isoafricanol	$C_{15}H_{26}O$		<i>Pellia epiphylla</i>	(175)	Sporophytes and spores

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ °cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
90	Leptographiol	C ₁₅ H ₂₆ O			<i>Pellia epiphylla</i>	(175)	Sporophytes
91	4β-Hydroxyisoafricanol	C ₁₅ H ₂₆ O		+10	<i>Pellia epiphylla</i>	(175)	Sporophytes
92	3α-Hydroxy-5α-acetoxyafrican-2(6)-en-4-one	C ₁₇ H ₂₄ O ₄			<i>Porella swartziana</i>	(848)	
93	1β,10β-Dihydroxyafrican-2-en-4-one	C ₁₅ H ₂₂ O ₃		+45.0	<i>Porella swartziana</i>	(126)	
94	3α,4β-Dihydroxyafrican-2(6)-en-5-one	C ₁₅ H ₂₂ O ₃		-40.0	<i>Porella swartziana</i>	(126) (848)	
95	3α,4α-Dihydroxyafrican-2(6)-en-4-one	C ₁₅ H ₂₂ O ₃			<i>Porella swartziana</i>	(126)	
96	Caespitenone	C ₁₃ H ₂₀ O ₂		-267	<i>Porella grandiloba</i> <i>Porella subobtusata</i>	(814) (569) (581)	
					<i>Porella swartziana</i>	(126) (848)	
97	14-Acetoxycaespenone	C ₁₇ H ₂₂ O ₄		-315.7	<i>Porella subobtusata</i>	(581)	
98	Swartzianin A	C ₁₅ H ₂₄		-117	<i>Porella subobtusata</i> <i>Porella swartziana</i>	(581) (848)	
99	<i>epi</i> -Swartzianin A	C ₁₅ H ₂₄		-116	<i>Pellia epiphylla</i>	(175)	Sporophytes
100	Swartzianin B	C ₁₅ H ₂₂ O		-184	<i>Porella swartziana</i>	(176) (126)	Gametophytes
101	Swartzianin C	C ₁₅ H ₂₂ O ₂	89-92	-368	<i>Porella swartziana</i>	(848) (126)	X-ray
102	Swartzianin D	C ₁₅ H ₂₀ O ₂	106-107	-153	<i>Porella swartziana</i>	(848) (126)	X-ray
103	Secoswartzianin A	C ₁₅ H ₂₀ O ₂	127-128	-39	<i>Porella grandiloba</i> <i>Porella subobtusata</i>	(848) (814) (581)	

104	Secoswartzianin B	C ₁₆ H ₂₄ O ₃	-193	<i>Porella swartziana</i> <i>Porella subobtusata</i> <i>Porella swartziana</i> <i>Porella swartziana</i>	(126) (848) (569) (126) (848)
105	2,3-Epoxysecoswartzianin A	C ₁₅ H ₂₀ O ₃	-16.5	<i>Porella swartziana</i>	(126)
106	Norsecoswartzianin	C ₁₄ H ₂₁ O ₃	-42.1	<i>Porella swartziana</i>	(126) (848)
107	Dehydroxynorsecoswartzianin	C ₁₄ H ₂₀ O ₂	-50	<i>Porella swartziana</i>	(126)
108	Aristolene	C ₁₅ H ₂₄		<i>Calypogeia muelleriana</i> <i>Calypogeia suecica</i> <i>Radula perrottetii</i>	(933) (934) (492)
109	Calarene (= 1(10)-Aristolene)	C ₁₅ H ₂₄		<i>Bazzania japonica</i> <i>Calypogeia muelleriana</i> <i>Calypogeia suecica</i>	(826) (485) (933) (934)
				<i>Marchantia paleacea</i> var. <i>diptera</i>	(492)
				<i>Marsupella aquatica</i>	(19)
				<i>Marsupidium epiphytum</i>	(635)
110	(-)-Calarene	C ₁₅ H ₂₄	-53.5	<i>Radula perrottetii</i>	(826)
				<i>Saccogyna viticulosa</i>	(276)
				<i>Symphogyna brasiliensis</i>	(492)
				<i>Tritomaria quinqueidentata</i>	(928)
				<i>Jungmannia infusca</i>	(587)
					(598)
				<i>Calypogeia suecica</i>	(934)
				<i>Marsupella emarginata</i>	(17)
				<i>Reboulia hemisphaerica</i>	(889)
				<i>Reboulia hemisphaerica</i>	(889)
111	<i>ent</i> -8 α -Methoxyaristol-9-ene	C ₁₆ H ₂₆ O			
112	<i>ent</i> -Aristol-9- <i>en</i> -8 α -ol	C ₁₅ H ₂₄ O			

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
113	<i>ent</i> -8 β -Methoxyaristol-9-ene	C ₁₆ H ₂₆ O			<i>Reboulia hemisphaerica</i>	(889)	
114	Aristolone	C ₁₅ H ₂₂ O			<i>Plagioclita circinalis</i>	(635) (897)	
115	4- <i>epi</i> -11-nor-Aristol-1(10),11-diene	C ₁₄ H ₂₀			<i>Bazzania japonica</i>	(485)	
116	4- <i>epi</i> -11-nor-Aristol-1,9,11-triene	C ₁₄ H ₁₈			<i>Bazzania japonica</i>	(485)	
117	4- <i>epi</i> -11-nor-Aristol-9,11-diene	C ₁₄ H ₂₀			<i>Bazzania japonica</i>	(485)	
118	(-)-Aristol-1(10)-en-12-ol	C ₁₃ H ₂₄ O			<i>Bazzania japonica</i>	(485)	
119	(-)-Aristol-1(10)-en-12-al	C ₁₃ H ₂₂ O			<i>Bazzania japonica</i>	(485)	
120	β -(α)-1,10-Epoxyaristolane	C ₁₅ H ₂₄ O			<i>Adelanthus lindenbergianus</i>	(116)	
121	Trinoranastreptene	C ₁₂ H ₁₆			<i>Bazzania praerupta</i>	(490)	
					<i>Barbilophozia floerkei</i>	(15)	
					<i>Lophozia ventricosa</i>	(486)	
122	Anastreptene	C ₁₃ H ₂₂			<i>Anastrophyllum donnianum</i>	(139)	
					<i>Barbilophozia floerkei</i>	(15)	
					<i>Bazzania involuta</i>	(72)	
					<i>Bazzania japonica</i>	(485)	
					<i>Bazzania praerupta</i>	(490)	
					<i>Bryopteris flicina</i>	(604)	
					<i>Calypogeia fissa</i>	(931)	
					<i>Calypogeia suecica</i>	(934)	
					<i>Chandonanthus hirtellus</i>	(224)	
						(423)	
						(490)	
						(494)	
					<i>Chiloscyphus coditus</i>	(72)	
					<i>Chiloscyphus triacanthus</i>	(72)	
					<i>Diplophyllum albicans</i>	(15)	
					<i>Heteroscyphus aselliformis</i>	(490)	

<i>Heteroscyphus</i> sp.	(635)
<i>Isotachis aubertii</i>	(288)
<i>Isotachis lyallii</i>	(73)
<i>Isotachis montana</i>	(73)
	(616)
<i>Jamesoniella autumnalis</i>	(109)
<i>Jamesoniella colorata</i>	(635)
	(901)
<i>Jamesoniella tasmanica</i>	(72)
<i>Kurzia makinoana</i>	(882)
<i>Kurzia trichoclados</i>	(922)
<i>Lepidozia concinna</i>	(72)
<i>Lepidozia spinosissima</i>	(72)
<i>Lophozia ventricosa</i>	(486)
<i>Marsupella alpina</i>	(17)
<i>Marsupella aquatica</i>	(19)
<i>Marsupella emarginata</i>	(17)
<i>Mylia taylorii</i>	(922)
<i>Mylia nuda</i>	(922)
<i>Odontoschisma denudatum</i>	(316)
	(882)
<i>Plagiochila asplenoides</i>	(14)
<i>Plagiochila elegans</i>	(470)
<i>Plagiochila fasciculata</i>	(72)
<i>Plagiochila longispina</i>	(331)
<i>Plagiochila stephensoniana</i>	(72)
Unidentified <i>Plagiochila</i> sp.	(494)
	(701)
<i>Saccogyna viticulosa</i>	(276)
<i>Tritomaria quinqueidentata</i>	(928)
<i>Calypogeia muelleriana</i>	(933)
(+)-Anastreptene	C ₁₅ H ₂₂

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
123	α -Gurjunene	$\text{C}_{15}\text{H}_{24}$			<i>Lepidozia concinna</i>	(72)	
					<i>Lunularia cruciata</i>	(79)	
					Unidentified <i>Jungermannia</i> sp.	(494)	
					<i>Marchantia polymorpha</i>	(79)	
					<i>Paraschistochila tuloides</i>	(72)	
					<i>Porella canariensis</i>	(179)	
					<i>Radula perrottetii</i>	(492)	
						(826)	
					<i>Schistochila balfouriana</i>	(72)	
					<i>Calypogeia muelleriana</i>	(933)	
124	β -Gurjunene	$\text{C}_{15}\text{H}_{24}$			<i>Conocephalum conicum</i>	(544)	
					Unidentified <i>Isotachis</i> sp. I	(73)	
					Unidentified <i>Isotachis</i> sp. II	(73)	
					<i>Paraschistochila tuloides</i>	(72)	
					<i>Riccardia eriocaula</i>	(72)	
					<i>Schistochila balfouriana</i>	(72)	
					<i>Schistochila reptata</i>	(72)	
					<i>Calypogeia azurea</i>	(816)	X-ray
					<i>Bazzania tridens</i>	(951)	
					<i>Conocephalum conicum</i>	(493)	
125	1,2-Dehydro-3-oxo- β -gurjunene	$\text{C}_{15}\text{H}_{20}\text{O}$	90-91.5	+3.33	<i>Frullania deplanata</i>	(78)	
					<i>Paraschistochila tuloides</i>	(72)	
					<i>Plagiochila sciophila</i>	(492)	
					<i>Porella vernicosa</i>	(637)	
					<i>Porella perrottetiana</i>	(424)	
					<i>Radula perrottetii</i>	(492)	
					<i>Schistochila balfouriana</i>	(72)	
126	Cyclocolorenone	$\text{C}_{15}\text{H}_{22}\text{O}$					

127	<i>ent</i> -Cyclocolorenone	$C_{15}H_{22}O$	Unidentified <i>Frullania</i> sp.	(843)
			<i>Porella canariensis</i>	(179)
	Viridiflorol	$C_{15}H_{26}O$	<i>Bazzania japonica</i>	(582)
			<i>Bazzania trilobata</i>	(604)
			<i>Lepidozia fauriana</i>	(485)
			<i>Lophozia ventricosa</i>	(715)
			<i>Plagiochila bifaria</i>	(645)
			<i>Plagiochila maderensis</i>	(486)
			<i>Plagiochila retrorsa</i>	(221)
			<i>Plagiochila stricta</i>	(221)
			<i>Bazzania trilobata</i>	(221)
128	<i>ent</i> -Viridiflorol	$C_{15}H_{26}O$	<i>Bazzania trilobata</i>	(582)
			<i>Bazzania trilobata</i>	(930)
	4-Dehydroviridiflorol	$C_{15}H_{24}O$	<i>Calypogeia muelleriana</i>	(933)
			<i>Conocephalum conicum</i>	(933)
			<i>Jungermannia infusca</i>	(544)
			<i>Kurzia trichoclados</i>	(600)
			<i>Mylia nuda</i>	(922)
			<i>Mylia nuda</i>	(922)
			<i>Mylia taylorii</i>	(922)
			<i>Bazzania japonica</i>	(922)
			<i>Bazzania trilobata</i>	(485)
			<i>Calypogeia muelleriana</i>	(930)
129	Ledene	$C_{15}H_{24}$	<i>Calypogeia fissa</i>	(933)
			<i>Calypogeia fissa</i>	(931)
	4-Dehydroviridiflorol	$C_{15}H_{24}O$	<i>Diplophyllum albicans</i>	(15)
			<i>Tritomaria quinquentata</i>	(928)
			<i>Frullania ptychantha</i>	(78)
			<i>Kurzia trichoclados</i>	(922)
			<i>Lepidozia vitrea</i>	(645)
			<i>Mylia nuda</i>	(922)
			<i>Mylia nuda</i>	(922)
			<i>Mylia nuda</i>	(922)
			<i>Mylia nuda</i>	(922)
			<i>Mylia nuda</i>	(922)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
	(-)-Ledene	$\text{C}_{15}\text{H}_{24}$			<i>Bazzania trilobata</i>	(930)	
					<i>Calypogeia fissa</i>	(931)	
					<i>Calypogeia muelleriana</i>	(933)	
					<i>Conocephalum conicum</i>	(544)	
					<i>Jackiella javanica</i>	(614)	
130	Isodene	$\text{C}_{15}\text{H}_{24}$			Unidentified <i>Jungermannia</i> sp.	(494)	
					<i>Lepidozia fauriana</i>	(645)	
	(+)-Isodene	$\text{C}_{15}\text{H}_{24}$			<i>Bazzania trilobata</i>	(930)	
					<i>Conocephalum conicum</i>	(544)	
					<i>Tritomaria quinqueidentata</i>	(928)	
131	(+)-3 α -Hydroxyledene	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Calypogeia muelleriana</i>	(933)	
132	Ledol	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Bazzania tridens</i>	(951)	
					<i>Frullania tamarisci</i>	(644)	
	(-)-Ledol	$\text{C}_{15}\text{H}_{26}\text{O}$		-3.7	<i>Bazzania tridens</i>	(955)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Cephaloziella recurvifolia</i>	(955)	
133	(+)-4(15)-Dehydroledol	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Lepicolea ochroleuca</i>	(478)	
134	Palustrol	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Mylia taylorii</i>	(569)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Lepicolea ochroleuca</i>	(478)	
135	(-)- β -Spathulene	$\text{C}_{15}\text{H}_{22}$			<i>Calypogeia muelleriana</i>	(933)	
136	Spathulenol	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Archilejeunea scutellata</i>	(72)	
					<i>Bazzania praerupta</i>	(490)	
					<i>Bazzania spiralis</i>	(490)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Cephaloziella recurvifolia</i>	(955)	

<i>Chandonanthus hirtellus</i>	(224)
	(423)
	(490)
<i>Chiloscyphus ammophilus</i>	(72)
<i>Chiloscyphus lingulatus</i>	(72)
<i>Dendromastigophora flagellifera</i>	(635)
<i>Frullania lobulata</i>	(78)
<i>Frullania media</i>	(78)
<i>Frullania serrata</i>	(490)
<i>Hymenophyton flabellatum</i>	(72)
<i>Jamesoniella autumnalis</i>	(109)
<i>Jamesoniella colorata</i>	(901)
<i>Jamesoniella tasmanica</i>	(72)
<i>Jungermannia fusiformis</i>	(882)
<i>Kurzia trichoclados</i>	(922)
<i>Lepidolaena clavigera</i>	(72)
<i>Lepidozia concinna</i>	(72)
<i>Lepidozia vitrea</i>	(645)
<i>Marchantia pileata</i>	(72)
<i>Mylia taylorii</i>	(922)
<i>Pallavicinia levierii</i>	(882)
<i>Paraschistochila tuloides</i>	(72)
<i>Pellia epiphylla</i>	(176)
<i>Plagiochila aerea</i>	(334)
<i>Plagiochila barteri</i>	(295)
<i>Plagiochila bifaria</i>	(221)
	(333)
<i>Plagiochila circinalis</i>	(72)
<i>Plagiochila carringtonii</i>	(697)
<i>Plagiochila fasciculata</i>	(72)

(continued)

			<i>Jackiella javanica</i>	(587)
				(608)
			<i>Jamesoniella tasmanica</i>	(872)
			<i>Lepidozia spinosissima</i>	(611)
				(616)
			<i>Porella acutifolia</i> subsp. <i>tosana</i>	(870)
			<i>Plagiochila buchtiniana</i>	(330)
			<i>Plagiochila cristata</i>	(911)
			<i>Plagiochila diversifolia</i>	(330)
			<i>Plagiochila ericicola</i>	(911)
			<i>Plagiochila fasciculata</i>	(607)
			<i>Plagiochila fruticosa</i>	(870)
			<i>Plagiochila longispina</i>	(330)
			<i>Plagiochila porelloides</i>	(866)
			<i>Plagiochila satoi</i>	(617)
			<i>Porella japonica</i>	(870)
			<i>Plagiochila sciophila</i>	(870)
			<i>Plagiochila yokogurensis</i>	(84)
			<i>Scapania nemorea</i>	(569)
			<i>Scapania stephanii</i>	(870)
			<i>Lepidozia fauriana</i>	(645)
			<i>Lepicolea ochroleuca</i>	(478)
			<i>Chandonanthus hirtellus</i>	(224)
			<i>Diplophyllum albicans</i>	(15)
			<i>Frullania tamarisci</i>	(644)
			<i>Lepidozia fauriana</i>	(645)
			<i>Lophozia ventricosa</i>	(486)
			<i>Plagiochila bifaria</i>	(221)
			<i>Plagiochila maderensis</i>	(221)
			<i>Plagiochila retrorsa</i>	(221)
			<i>Plagiochila stricta</i>	(221)
137	(-)-Isospathulenol	C ₁₅ H ₂₄ O		
138	<i>ent</i> -3 β -Hydroxyspathulenol	C ₁₅ H ₂₄ O ₂		
139	Globulol	C ₁₅ H ₂₆ O	-9.9	

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
	<i>ent</i> -Globulol	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Bazzania madagassa</i>	(293)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Calypogeia fissa</i>	(931)	
					<i>Calypogeia muelleriana</i>	(72)	
					<i>Jackiella javanica</i>	(608)	
					<i>Kurzia trichoclados</i>	(922)	
					<i>Mylia nuda</i>	(922)	
					<i>Mylia taylorii</i>	(569)	
						(922)	
					<i>Neotrichocolea bissetii</i>	(891)	
				+20.5	<i>Pallavicinia subciliata</i>	(891)	
				+35.9	<i>Pellia epiphylla</i>	(176)	
					<i>Plagiochila ovalifolia</i>	(891)	
				+31.4	<i>Plagiochila yokogurensis</i>	(84)	
					<i>Tritomaria quinqueidentata</i>	(928)	
140	4(15)-Dehydroglobulol	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Mylia nuda</i>	(922)	
					<i>Mylia taylorii</i>	(922)	
141	(+)-4(15)-Dehydroglobulol Myli-4(15)-ene	$\text{C}_{15}\text{H}_{24}\text{O}$ $\text{C}_{15}\text{H}_{22}$			<i>Mylia taylorii</i>	(569)	
					<i>Mylia nuda</i>	(922)	
					<i>Radula holttii</i>	(223)	
					<i>Mylia taylorii</i>	(922)	
142	(-)-(1 <i>R</i> *,5 <i>S</i> *,6 <i>R</i> *,7 <i>S</i> *,10 <i>S</i> *)-Myli-4(15)-ene	$\text{C}_{15}\text{H}_{22}$			<i>Mylia nuda</i>	(922)	
					<i>Mylia taylorii</i>	(922)	
143	(-)-(1 <i>S</i> ,5 <i>R</i> ,6 <i>R</i> ,7 <i>S</i> ,10 <i>S</i>)-Myli-4(15)-en-3-one Myliol	$\text{C}_{15}\text{H}_{20}\text{O}$ $\text{C}_{15}\text{H}_{22}\text{O}$			<i>Kurzia trichoclados</i>	(922)	
					<i>Mylia nuda</i>	(922)	
					<i>Mylia taylorii</i>	(922)	
					<i>Mylia taylorii</i>	(569)	

144	Dihydromylione A	C ₁₅ H ₂₂ O	<i>Kurzia trichoclados</i> (922)
145	Taylorione	C ₁₅ H ₂₂ O	<i>Mylia nuda</i> (922)
			<i>Mylia taylorii</i> (922)
			<i>Kurzia trichoclados</i> (922)
			<i>Mylia nuda</i> (922)
			<i>Mylia taylorii</i> (922)
146	(-)-Taylorione	C ₁₅ H ₂₂ O	<i>Mylia taylorii</i> (569)
147	3-Acetoxytaylorione	C ₁₇ H ₂₆ O ₃	<i>Mylia taylorii</i> (922)
	α -Taylorione	C ₁₅ H ₂₂ O	<i>Mylia nuda</i> (922)
148	(-)-(6R,7S)- α -Taylorione	C ₁₅ H ₂₂ O	<i>Mylia taylorii</i> (922)
149	1,10-Dioxotayloriane	C ₁₅ H ₂₄ O ₂	<i>Lepicolea ochroleuca</i> (478)
150	Myltaylorione A	C ₃₀ H ₄₂ O ₂	<i>Mylia taylorii</i> (569)
151	Myltaylorione B	C ₃₀ H ₄₂ O ₂	<i>Mylia taylorii</i> (569)
	(-)-(7S)-(E)-Taylorpyran	C ₁₅ H ₂₂ O	<i>Kurzia trichoclados</i> (922)
152	(-)-(6S,7S,10R)-Taylorcyclane	C ₁₅ H ₂₂ O	<i>Mylia nuda</i> (922)
153	(5S*,7S*)-Taylorfuran	C ₁₅ H ₂₄ O ₂	<i>Mylia nuda</i> (922)
154	(1R*,4S*,5S*,6R*,7S*,9R*)- Taynudol	C ₁₅ H ₂₂ O	<i>Mylia taylorii</i> (922)
155	Tridensenone	C ₁₅ H ₂₀ O	<i>Mylia nuda</i> (922)
			<i>Mylia taylorii</i> (922)
156	Aromadendrene	C ₁₅ H ₂₄	<i>Bazzania japonica</i> (485)
			<i>Bazzania tridens</i> (846)
			<i>Drepanolejeunea</i> (247)
			<i>madagascariensis</i> (78)
			<i>Frullania lobulata</i> (73)
			<i>Isotachis laylii</i> (645)
			<i>Lepidozia fauriana</i> (79)
			<i>Marchantia polymorpha</i> (922)
			<i>Mylia nuda</i> (922)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
					<i>Mylia taylorii</i>	(922)	
					<i>Plagiochila bifaria</i>	(221)	
					<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Schistochila balfouriana</i>	(72)	
					<i>Tritomaria polita</i>	(18)	
		$\text{C}_{15}\text{H}_{24}$			<i>Calypogeia fissa</i>	(931)	
	(-)-Aromadendrene				<i>Calypogeia muelleriana</i>	(933)	
157	9-Aromadendrene	$\text{C}_{15}\text{H}_{24}$			<i>Calypogeia muelleriana</i>	(933)	
158	<i>allo</i> -Aromadendrene	$\text{C}_{15}\text{H}_{24}$			<i>Bazzania trilobata</i>	(930)	
					<i>Chandonanthus hirtellus</i>	(423)	
						(494)	
					<i>Frullania probosciphora</i>	(78)	
					<i>Kurzia trichoclados</i>	(922)	
					<i>Leptozia fauriana</i>	(645)	
					<i>Marchesinia mackaii</i>	(220)	
					<i>Marsupella emarginata</i>	(17)	
					<i>Mylia nuda</i>	(922)	
					<i>Mylia taylorii</i>	(922)	
					<i>Pellia endiviifolia</i>	(492)	
					<i>Plagiochila sciophila</i>	(492)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Radula carringtonii</i>	(223)	
					<i>Radula perrottetii</i>	(826)	
					<i>Tritomaria polita</i>	(18)	
					<i>Tritomaria quinqueidentata</i>	(928)	
	(-)- <i>allo</i> -Aromadendrene	$\text{C}_{15}\text{H}_{24}$			<i>Calypogeia muelleriana</i>	(933)	

159	9- <i>allo</i> -Aromadendrene	C ₁₅ H ₂₄	<i>Bazzania trilobata</i> (930) <i>Calypogeia fissa</i> (931) <i>Calypogeia muelleriana</i> (933) <i>Frullania ptychantha</i> (78) <i>Barbilophozia floerkei</i> (15) <i>Saccogyna viticulosa</i> (276)
160	<i>allo</i> -Aromadendra-4(15),10(14)-diene (+)- <i>allo</i> -Aromadendra-4(15),10(14)-diene	C ₁₅ H ₂₂ C ₁₅ H ₂₂	
161	<i>ent</i> -1 β -Hydroxy- <i>allo</i> -aromadendrene	C ₁₅ H ₂₄ O	<i>Lepidozia setigera</i> (347)
162	<i>ent</i> -10 α -Hydroxyaromadendr-1-ene	C ₁₅ H ₂₄ O	<i>Lepidozia setigera</i> (347)
163	(-)-Aromadendra-1(10),3-diene	C ₁₅ H ₂₂	<i>Plagiochila asplenoides</i> (14) Unidentified <i>Plagiochila</i> sp. (494)
164	Aromadendra-1(10),4-diene	C ₁₅ H ₂₂	<i>Kurzia trichoclados</i> (922) <i>Mylia nuda</i> (922) <i>Mylia taylorii</i> (922)
165	(6 <i>R</i> ,7 <i>S</i>)-Aromadendra-1(10),4-diene Aromadendra-1(10),4(15)-diene	C ₁₅ H ₂₂ C ₁₅ H ₂₂	<i>Diplophyllum albicans</i> (15) <i>Kurzia trichoclados</i> (922) <i>Mylia nuda</i> (922) <i>Mylia taylorii</i> (922)
166	(+)-(5 <i>S</i> *,6 <i>S</i> *,7 <i>S</i> *)-Aromadendra-1(10),4(15)-diene Aromadendra-4,10(14)-diene	C ₁₅ H ₂₂ C ₁₅ H ₂₂	<i>Diplophyllum albicans</i> (15) <i>Mylia nuda</i> (922) <i>Mylia taylorii</i> (922)
167	(+)-(1 <i>S</i> ,6 <i>R</i> ,7 <i>S</i>)-Aromadendra-4,10(14)-diene Aromadendra-4,9-diene	C ₁₅ H ₂₂ C ₁₅ H ₂₂	<i>Diplophyllum albicans</i> (15) <i>Kurzia trichoclados</i> (922) <i>Mylia nuda</i> (922) <i>Mylia taylorii</i> (922)
168	(1 <i>S</i> ,6 <i>R</i> ,7 <i>S</i>)-Aromadendra-4,9-diene (+)-Aromadendra-4(15),10(14)-dien-1-ol	C ₁₅ H ₂₂ C ₁₅ H ₂₂ O	<i>Saccogyna viticulosa</i> (276)
169	(-)-Aromadendran-5-ol	C ₁₅ H ₂₆ O	<i>Conocephalum conicum</i> (544)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
170	(+)-Aromadendr-4-en-12-ol	C ₁₅ H ₂₄ O			<i>Conocephalum conicum</i>	(544)	
171	<i>ent</i> -4 β ,10 α -Dihydroxyaromadendrane	C ₁₅ H ₂₆ O ₂		+18.2	<i>Bazzania madagassa</i> <i>Jackiella javanica</i> <i>Lepidozia fauriana</i> <i>Plagiochila ovalifolia</i> <i>Plagiochila pulcherrima</i> <i>Lepicolea ochroleuca</i>	(293) (614) (747) (579) (477) (478)	
172	<i>ent</i> -4 β -Hydroxy-10 α -methoxy-aromadendrane	C ₁₆ H ₂₈ O ₂		+9.2	<i>Tylimanthus renifolius</i>	(213)	
173	9-Acetoxy-10-hydroxyaromadendrane	C ₁₇ H ₂₈ O ₃			<i>Heteroscyphus codinus</i>	(873)	X-ray
174	5 β -Hydroxy- <i>ent</i> -aromadendr-1-en-3-one	C ₁₅ H ₂₂ O ₂		+119.9	<i>Lepidozia spinosissima</i>	(72) (616)	
175	1,5-Epoxyaromadendra-3-one	C ₁₅ H ₂₂ O ₂		+37.1	<i>Heteroscyphus codinus</i>	(617)	
176	4(15)-Aromadendren-12,5-olide	C ₁₅ H ₂₀ O ₂	105-106	+61.6	<i>Chiloscyphus subporosus</i>	(606)	
177	Aromadendrane-guaianolide dimer	C ₃₀ H ₄₀ O ₄		+88.8	<i>Chiloscyphus subporosus</i>	(606)	
178	Planotriol	C ₁₅ H ₂₄ O ₃	129-131	+8.6	<i>Heteroscyphus planus</i>	(562)	Cell culture
179	Planotriol monoacetate	C ₁₇ H ₂₆ O ₄		+13.3	<i>Heteroscyphus planus</i>	(562)	Cell culture
180	Planotriol diacetate	C ₁₉ H ₂₈ O ₅		-1.55	<i>Heteroscyphus planus</i>	(562)	Cell culture
181	<i>ent</i> -2,3-Diacetoxy-10 α ,15 α -epoxy-2,3- <i>seco</i> - <i>allo</i> -aromadendr-4(14)-ene	C ₁₉ H ₂₈ O ₅		+19.8	<i>Heteroscyphus planus</i>	(562)	Cell culture
182	<i>ent</i> -Deacetylplagiochiline C	C ₁₇ H ₂₄ O ₄		+13.0	<i>Heteroscyphus planus</i>	(562)	Cell culture
183	Plagiochiline A	C ₁₉ H ₂₆ O ₆		+34	<i>Heteroscyphus planus</i> <i>Plagiochila adianthoides</i> <i>Palgtochila aerea</i> <i>Plagiochila ovalifolia</i> <i>Plagiochila pulcherrima</i> <i>Plagiochila yokogurensis</i>	(562) (911) (334) (84) (477) (84)	Cell culture

184	Plagiochiline B	C ₂₁ H ₂₈ O ₈	<i>Plagiochila pulcherrima</i>	(477)
185	Plagiochiline C	C ₁₉ H ₂₆ O ₅	<i>Plagiochila aerea</i>	(334)
			<i>Plagiochila asplenoides</i>	(604)
			<i>Plagiochila atlantica</i>	(334)
				(691)
			<i>Plagiochila cristata</i>	(911)
			<i>Plagiochila elegans</i>	(470)
			<i>Plagiochila ericicola</i>	(911)
			<i>Plagiochila incurvicolla</i>	(558)
			<i>Plagiochila ovalifolia</i>	(84)
			<i>Plagiochila porelloides</i>	(762)
			<i>Plagiochila pulcherima</i>	(477)
			<i>Plagiochila satoi</i>	(617)
			<i>Plagiochila yokogurensis</i>	(84)
186	Plagiochiline D		<i>Plagiochila porelloides</i>	(866)
187	Plagiochiline E	C ₂₃ H ₃₀ O ₁₀	<i>Plagiochila incurvicolla</i>	(558)
188	Plagiochiline H	C ₁₇ H ₂₄ O ₃	<i>Plagiochila adanthoides</i>	(911)
			<i>Plagiochila cristata</i>	(911)
			<i>Plagiochila elegans</i>	(470)
			<i>Plagiochila ericicola</i>	(911)
			<i>Plagiochila yokogurensis</i>	(84)
189	Plagiochiline L	C ₁₇ H ₂₂ O ₅	<i>Heteroscyphus planus</i>	(310)
190	Plagiochiline M	C ₁₈ H ₂₄ O ₅	<i>Heteroscyphus planus</i>	(310)
191	Plagiochiline N	C ₁₅ H ₁₆ O ₅	<i>Plagiochila ovalifolia</i>	(579)
192	Plagiochiline O	C ₂₁ H ₂₈ O ₈	<i>Plagiochila cristata</i>	(911)
193	Plagiochiline P	C ₂₁ H ₃₀ O ₇	<i>Plagiochila asplenoides</i>	(441)
			<i>Plagiochila cristata</i>	(911)
194	Plagiochiline Q	C ₁₅ H ₂₀ O ₂	<i>Plagiochila cristata</i>	(911)
195	Plagiochiline R	C ₂₁ H ₂₈ O ₈	<i>Plagiochila ericicola</i>	(911)
196	Plagiochiline S	C ₁₉ H ₂₆ O ₅	<i>Plagiochila adanthoides</i>	(911)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
197	Plagiochiline T	$\text{C}_{19}\text{H}_{24}\text{O}_6$			<i>Plagiochila carringtonii</i>	(697)	
198	Plagiochiline T dimethyl acetal	$\text{C}_{21}\text{H}_{30}\text{O}_7$			<i>Plagiochila carringtonii</i>	(697)	
199	Plagiochiline U	$\text{C}_{20}\text{H}_{26}\text{O}_7$			<i>Plagiochila carringtonii</i>	(697)	
200	(+)-Plagiochiline W	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Plagiochila asplenoides</i>	(14)	
201	(+)-Plagiochiline X	$\text{C}_{15}\text{H}_{20}\text{O}$			<i>Plagiochila asplenoides</i>	(14)	
202	Plagiochiline V	$\text{C}_{20}\text{H}_{26}\text{O}_8$			<i>Plagiochila porelloides</i>	(762)	
203	Plagiochilide	$\text{C}_{15}\text{H}_{20}\text{O}_2$			<i>Plagiochila asplenoides</i>	(14)	
					<i>Plagiochila yokogurensis</i>	(84)	
204	Isoplagiochilide	$\text{C}_{15}\text{H}_{20}\text{O}_2$		+55	<i>Plagiochila elegans</i>	(470)	
				+82.5	<i>Plagiochila squamulosa</i> var. <i>sinuosa</i>	(911)	
205	Ovalifolene	$\text{C}_{19}\text{H}_{26}\text{O}_3$			<i>Plagiochila ovalifolia</i>	(529)	
206	Ovalifoltenal	$\text{C}_{19}\text{H}_{24}\text{O}_6$			<i>Plagiochila asplenoides</i>	(604)	
207	9,10-Dihydroovalifolienal	$\text{C}_{19}\text{H}_{26}\text{O}_6$			<i>Plagiochila adianthoides</i>	(911)	
208	Plagiochilal A (= Hanegokedial)	$\text{C}_{15}\text{H}_{22}\text{O}_2$			<i>Plagiochila asplenoides</i>	(604)	
209	Henegoketral	$\text{C}_{15}\text{H}_{18}\text{O}_3$			<i>Plagiochila asplenoides</i>	(604)	
210	Methoxyplagiochiline A ₂	$\text{C}_{18}\text{H}_{26}\text{O}_5$		+9.0	<i>Heteroscyphus planus</i>	(562)	Cell culture
211	Acetoxyisoplagiochilide	$\text{C}_{17}\text{H}_{22}\text{O}_4$		+14.3	<i>Plagiochila ovalifolia</i>	(579)	
212	Neofuranoplagiochilal	$\text{C}_{15}\text{H}_{16}\text{O}_2$		−81.2	Unidentified <i>Plagiochila</i> sp.	(701)	
213	Plagiochiline A-15-yl octanoate	$\text{C}_{27}\text{H}_{40}\text{O}_8$			<i>Plagiochila ovalifolia</i>	(881)	
						(888)	
214	Plagiochiline A-15-yl decanoate	$\text{C}_{29}\text{H}_{44}\text{O}_8$			<i>Plagiochila porelloides</i>	(866)	
215	Plagiochiline A-15-yl (4Z)-decanoate	$\text{C}_{29}\text{H}_{42}\text{O}_8$			<i>Plagiochila ovalifolia</i>	(881)	
					<i>Plagiochila porelloides</i>	(866)	
216	Plagiochiline A-15-yl hexanoate	$\text{C}_{25}\text{H}_{36}\text{O}_8$			<i>Plagiochila ovalifolia</i>	(84)	
						(881)	

217	14-Hydroxyplagiochiline A-15-yl (2 <i>E</i> ,4 <i>E</i> ,8 <i>Z</i>)-tetradecatrienoate	C ₃₃ H ₄₆ O ₉	<i>Plagiochila ovalifolia</i>	(44) (881)
218	14-Hydroxyplagiochiline A-15-yl (2 <i>E</i> ,4 <i>E</i>)-dodecadienoate	C ₃₁ H ₄₄ O ₉	<i>Plagiochila ovalifolia</i>	(888) (44) (881) (888)
219	14-Hydroxyplagiochiline A-15-yl (2 <i>E</i>)-decenoate	C ₃₁ H ₄₆ O ₉	<i>Plagiochila ovalifolia</i>	(44) (881)
220	14-Hydroxyplagiochiline A-15-yl (<i>E</i>)-4-hydroxycinnamate	C ₂₈ H ₃₂ O ₁₀	<i>Plagiochila ovalifolia</i>	(44) (881)
221	14-Hydroxyplagiochiline A-15-yl (<i>Z</i>)-4-hydroxycinnamate	C ₂₈ H ₃₂ O ₁₀	<i>Plagiochila ovalifolia</i>	(44) (881)
222	15-Hydroxyplagiochiline A-14-yl (<i>E</i>)-4-hydroxycinnamate	C ₂₈ H ₃₂ O ₁₀	<i>Plagiochila ovalifolia</i>	(44) (881)
223	15-Hydroxyplagiochiline A-14-yl (<i>Z</i>)-4-hydroxycinnamate	C ₂₈ H ₃₂ O ₁₀	<i>Plagiochila ovalifolia</i>	(44) (881)
224	Chandolide	C ₁₅ H ₂₀ O ₂	<i>Chandonanthus hirtellus</i>	(422) (423) X-ray
225	(+)-Zierene (= Deoxysaccogynol)	C ₁₅ H ₂₂	<i>Plagiochila bifaria</i> <i>Plagiochila maderensis</i> <i>Plagiochila retrorsa</i> <i>Plagiochila stricta</i> <i>Saccogyna viticulosa</i>	(221) (221) (221) (221) (164) (276)
226	(+)-Isozieren	C ₁₅ H ₂₂	<i>Saccogyna viticulosa</i>	(276)
227	(+)-Saccogynol	C ₁₅ H ₂₂ O	<i>Saccogyna viticulosa</i>	(164) (276) (276)
228	Isosaccogynol	C ₁₅ H ₂₂ O	<i>Saccogyna viticulosa</i>	(276)
229	Isosaccogynone	C ₁₅ H ₂₀ O	<i>Saccogyna viticulosa</i>	(276)
230	1,4-Dimethylazulene	C ₁₂ H ₁₂	<i>Barbilophozia floerkei</i>	(15)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
231	(+)-1,2,3,6-Tetrahydro-1,4-dimethylazulene	$\text{C}_{12}\text{H}_{16}$			<i>Calypogeia azurea</i>	(816)	
					<i>Calypogeia muelleriana</i>	(933)	
					<i>Plagiochila diversifolia</i>	(330)	
					<i>Plagiochila longispina</i>	(330)	
					<i>Barbilophozia floerkei</i>	(15)	
232	(-)-2,3,3a,4,5,6-Hexahydro-1,4-dimethylazulen-4-ol	$\text{C}_{12}\text{H}_{18}\text{O}$			<i>Barbilophozia floerkei</i>	(15)	
233	Vetivazulene	$\text{C}_{12}\text{H}_{18}$			<i>Lepidozia virea</i>	(645)	
234	α -Barbatene	$\text{C}_{13}\text{H}_{24}$			<i>Anastrophyllum auritum</i>	(976)	
					<i>Asterella echinella</i>	(492)	
					<i>Bazzania decrescens</i>	(291)	
					<i>Bazzania trilobata</i>	(17)	
						(930)	
					<i>Isotachis aubertii</i>	(288)	
					<i>Kurzia trichoclados</i>	(922)	
					<i>Lepidozia virea</i>	(645)	
					<i>Marsupella aquatica</i>	(19)	
					<i>Marsupella emarginata</i>	(15)	
					<i>Mylia taylori</i>	(922)	
					<i>Metacalypogeia alternifolia</i>	(748)	
					<i>Plagiochila asplenoides</i>	(14)	
					<i>Plagiochila circinalis</i>	(72)	
					<i>Plagiochila sciophila</i>	(492)	
					<i>Scapania undulata</i>	(16)	
					<i>Schistochila ciliata</i>	(72)	
					<i>Tylimanthus saccatus</i>	(72)	

235	(+)- α -Barbatene	$C_{15}H_{24}$	<i>Lepidozia reptans</i>	(681)
			<i>Reboulia hemisphaerica</i>	(929)
	β -Barbatene	$C_{15}H_{24}$	<i>Gymnomitrium obtusum</i>	(929)
			<i>Apometzgeria pubescens</i>	(882)
			<i>Asterella echinella</i>	(492)
			<i>Asterella venosa</i>	(492)
			<i>Barbilophozia barbata</i>	(596)
			<i>Barbilophozia floerkei</i>	(583)
			<i>Barbilophozia hatcheri</i>	(596)
			<i>Bazzania harpago</i>	(490)
			<i>Bazzania involuta</i>	(72)
			<i>Bazzania japonica</i>	(485)
			<i>Bazzania madagassa</i>	(291)
				(293)
			<i>Bazzania nitida</i>	(289)
			<i>Bazzania novae-zealandiae</i>	(72)
			<i>Bazzania tayloriana</i>	(72)
			<i>Bazzania tridens</i>	(951)
			<i>Calypogeia muelleriana</i>	(933)
			<i>Calypogeia suecica</i>	(934)
			<i>Chiloscyphus lingulatus</i>	(72)
			<i>Chiloscyphus triacanthus</i>	(72)
			<i>Cuspidatula monodon</i>	(72)
			<i>Cylindrocolea recurvifolia</i>	(958)
			<i>Diplophyllum albicans</i>	(15)
			<i>Dumortiera hirsuta</i>	(78)
				(96)
				(490)
			<i>Frullania anomala</i>	(492)
			<i>Frullania falciloba</i>	(78)
				(78)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
					<i>Frullania scandens</i>	(78)	
					<i>Frullania chevalierii</i>	(78)	
					<i>Frullania squarrosula</i>	(72)	
					<i>Heteroscyphus</i> species	(635)	
					<i>Jamesoniella autumnalis</i>	(109)	
					<i>Jamesoniella colorata</i>	(635)	
						(901)	
					<i>Jamesoniella tasmanica</i>	(72)	
					<i>Jungermannia truncata</i>	(601)	
					<i>Kurzia makinoana</i>	(882)	
					<i>Kurzia trichoclados</i>	(922)	
					<i>Lejeunea aquatica</i>	(878)	
					<i>Lejeunea parva</i>	(882)	
					<i>Lepidozia concinna</i>	(72)	
					<i>Lepidozia fauriana</i>	(645)	
					<i>Lepidozia vitrea</i>	(645)	
					<i>Lophocolea bidentata</i>	(679)	
					<i>Lophozia ventricosa</i>	(486)	
					<i>Marchantia polymorpha</i>	(492)	
					<i>Marchantia tosona</i>	(79)	
					<i>Makinoa crispata</i>	(492)	
					<i>Marsupella aquatica</i>	(17)	
						(19)	
					<i>Marsupella emarginata</i>	(15)	
						(17)	
					<i>Marsupidium epiphytum</i>	(635)	
					<i>Metacalypogeia alternifolia</i>	(748)	

<i>Metacalypogeia cordifolia</i>	(882)
<i>Mylia taylorii</i>	(894)
<i>Plagiochasma pterospermum</i>	(922)
<i>Plagiochila asplenoides</i>	(314)
	(14)
	(604)
<i>Plagiochila buchtiniana</i>	(330)
<i>Plagiochila carringtonii</i>	(697)
<i>Plagiochila circinalis</i>	(72)
	(635)
<i>Plagiochila diversifolia</i>	(330)
<i>Plagiochila elegans</i>	(470)
<i>Plagiochila longispina</i>	(330)
<i>Plagiochila ovalifolia</i>	(701)
<i>Plagiochila porelloides</i>	(762)
<i>Plagiochila retrospectans</i>	(72)
<i>Plagiochila sciophila</i>	(492)
Unidentified <i>Plagiochila</i> sp.	(494)
<i>Preissia quadrata</i>	(74)
<i>Radula perrottetii</i>	(492)
<i>Reboulia hemisphaerica</i>	(492)
<i>Scapania javanica</i>	(490)
<i>Scapania undulata</i>	(16)
<i>Schistochila ciliata</i>	(72)
<i>Trichocolea pluma</i>	(494)
<i>Tritomaria quinqueidentata</i>	(928)
<i>Trocholejeunea sandvicensis</i>	(492)
	(539)
<i>Wettsteinia schusterana</i>	(70)
<i>Anastrophyllum auritum</i>	(976)
<i>Bazzania trilobata</i>	(930)

C₁₅H₂₄

(-)-β-Barbatene

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
236	Gymnomitri-3(15),4-diene (-)-Gymnomitri-3(15),4-diene	$\text{C}_{15}\text{H}_{22}$ $\text{C}_{15}\text{H}_{22}$			<i>Gymnomitrium obtusum</i>	(929)	
					<i>Lepidozia reptans</i>	(681)	
					<i>Reboulia hemisphaerica</i>	(929)	
					<i>Bazzania harpago</i>	(490)	
					<i>Marsupella emarginata</i>	(15)	
237	3-Gymnomitren-15-ol	$\text{C}_{15}\text{H}_{24}\text{O}$		+27		(17)	
					<i>Reboulia hemisphaerica</i>	(929)	
					<i>Bazzania harpago</i>	(490)	
					<i>Jamesoniella colorata</i>	(635)	
						(901)	
238	15- <i>nor</i> -3-Gymnomitrone	$\text{C}_{14}\text{H}_{22}\text{O}$			<i>Jungermannia infusca</i>	(599)	
					<i>Jungermannia truncata</i>	(136)	
						(477)	
					<i>Lejeunea aquatica</i>	(878)	
					<i>Reboulia hemisphaerica</i>	(492)	
239 240	Gymnomitrone Gymnomitrol	$\text{C}_{15}\text{H}_{22}\text{O}$ $\text{C}_{15}\text{H}_{24}\text{O}$			<i>Jungermannia truncata</i>	(136)	
						(477)	
					<i>Marsupella emarginata</i>	(15)	
					<i>Gymnomitrium obtusum</i>	(929)	
					<i>Bazzania nitida</i>	(289)	
241	(+)Gymnomitrol	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Bazzania trilobata</i>	(715)	
					<i>Reboulia hemisphaerica</i>	(436)	
						(492)	
					<i>Bazzania trilobata</i>	(582)	
						(930)	
241	(+)Gymnomitrol acetate	$\text{C}_{15}\text{H}_{26}\text{O}_2$			<i>Gymnomitrium obtusum</i>	(929)	
					<i>Reboulia hemisphaerica</i>	(929)	
					<i>Gymnomitrium obtusum</i>	(929)	

242	(+)-Isogymnomitrol	$C_{15}H_{24}O$		<i>Bazzania trilobata</i> (930)
243	(+)-Gymnomitr-3(15)-en-4 α -ol	$C_{15}H_{24}O$		<i>Gymnomitron obtusum</i> (929)
				<i>Bazzania harpago</i> (490)
				<i>Plagiochasma pterospermum</i> (314)
				<i>Reboulia hemisphaerica</i> (492)
244	Gymnomitr-3(15)-en-4 β -ol	$C_{15}H_{24}O$		(929)
				<i>Marsupella emarginata</i> (15)
				(17)
				<i>Plagiochila asplenoides</i> (14)
				<i>Plagiochasma pterospermum</i> (314)
			-33.8	<i>Plagiochila asplenoides</i> (441)
245	(-)-Gymnomitr-3(15)-en-4 β -ol	$C_{15}H_{24}O$		(604)
246	(-)-Gymnomitr-3(15)-en-4 β -yl acetate	$C_{17}H_{26}O_2$		(17)
	Gymnomitr-3(15)-en-5 α -ol	$C_{15}H_{24}O$		<i>Cylindrocolea recurvifolia</i> (958)
				<i>Isotachis aubertii</i> (288)
247	(+)-Gymnomitr-3(15)-en-4-one	$C_{15}H_{22}O$		<i>Reboulia hemisphaerica</i> (436)
				<i>Bazzania harpago</i> (490)
				<i>Plagiochasma pterospermum</i> (314)
				<i>Reboulia hemisphaerica</i> (492)
				(929)
248	(+)-Gymnomitran-4-one	$C_{15}H_{24}O$		<i>Marsupella emarginata</i> (15)
				<i>Plagiochasma pterospermum</i> (314)
249	Gymnomitr-3(15)-en-9-one	$C_{15}H_{22}O$	-26.7	<i>Reboulia hemisphaerica</i> (929)
				<i>Bazzania trilobata</i> (715)
				(15)
250	3(15)-Epoxygymnomitran	$C_{15}H_{24}O$		<i>Marsupella emarginata</i> (15)
251	(-)-3 β ,15 β -Epoxy-4 β -acetoxy- gymnomitran	$C_{17}H_{26}O_3$	-4.8	<i>Reboulia hemisphaerica</i> (889)
				<i>Jungmannia truncata</i> (601)
				<i>Marsupella emarginata</i> (15)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
252	(-)-3 α ,15 α -Epoxyygymnomitr-4 β -acetoxyygymnomitrane	$\text{C}_{17}\text{H}_{26}\text{O}_3$			<i>Marsupella emarginata</i>	(15)	
253	(-)-4 β ,5 β -Diacetoxyygymnomitr-3(15)-ene	$\text{C}_{19}\text{H}_{28}\text{O}_4$			<i>Marsupella emarginata</i>	(15)	
254	(+)-5 β -Acetoxyygymnomitr-3(15)-ene	$\text{C}_{17}\text{H}_{26}\text{O}_2$			<i>Marsupella emarginata</i>	(15)	
255	(-)-15-Acetoxyygymnomitr-3-ene	$\text{C}_{17}\text{H}_{24}\text{O}_2$			<i>Marsupella emarginata</i>	(15)	
256	(+)- α -Barbatenol	$\text{C}_{15}\text{H}_{20}\text{O}$			<i>Marsupella emarginata</i>	(15)	
257	Gymnomitr-3(15)-en-12-al	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Heteroscyphus species</i>	(635)	
258	Gymnomitr-3(15)-en-12-ol	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Chiloscyphus mittenianus</i>	(347)	
259	Gymnomitr-3(15)-en-12-oic acid	$\text{C}_{15}\text{H}_{22}\text{O}_2$			<i>Chiloscyphus mittenianus</i>	(347)	
260	Isobazzanene	$\text{C}_{15}\text{H}_{24}$			<i>Asterella echinella</i>	(492)	
					<i>Bazzania madagassa</i>	(291)	
					<i>Bazzania nitida</i>	(293)	
					<i>Bazzania nitida</i>	(289)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Gymnomitron obtusum</i>	(929)	
					<i>Kurzia trichoclados</i>	(922)	
					<i>Lepidozia borneensis</i>	(490)	
					<i>Lepidozia vitrea</i>	(645)	
					<i>Makinoa crispata</i>	(492)	
					<i>Marchantia tosona</i>	(492)	
					<i>Marsupella aquatica</i>	(17)	
					<i>Marsupella aquatica</i>	(19)	
					<i>Marsupella emarginata</i>	(17)	
					<i>Mylia taylorii</i>	(922)	
					<i>Reboulia hemisphaerica</i>	(929)	
					<i>Scapania undulata</i>	(16)	

261	β -Bazzanene	$C_{15}H_{24}$	<i>Bazzania decrescens</i> (291) <i>Bazzania involuta</i> (72) <i>Bazzania novae-zealandiae</i> (72) <i>Bazzania tayloriana</i> (72) <i>Bazzania tridens</i> (951) <i>Bazzania trilobata</i> (582) <i>Diplophyllum albicans</i> (15) <i>Frullania tamarisci</i> (644) <i>Frullania falciloba</i> (78) <i>Frullania media</i> (78) <i>Frullania probosciphora</i> (78) <i>Frullania squarrosula</i> (78) <i>Lepidozia borneensis</i> (490) <i>Lepidozia fairiana</i> (645) <i>Makinoa crispata</i> (492) <i>Mylia taylorii</i> (922) <i>Plagiiochasma pterospermum</i> (314) <i>Plagiiochila asplenoides</i> (14) <i>Plagiiochila circinalis</i> (635) <i>Reboulia hemisphaerica</i> (897) <i>Schistochila ciliata</i> (929) <i>Bazzania trilobata</i> (72) <i>Bazzania pompeana</i> (930) <i>Bazzania pompeana</i> (84) <i>Frullania squarrosula</i> (78) <i>Bazzania pompeana</i> (84) <i>Bazzania pompeana</i> (84) <i>Frullania falciloba</i> (84) (613)
262	(+)- β -Bazzanene Bazzanenol	$C_{15}H_{24}$ $C_{15}H_{24}O$	
263	Bazzanenyl caffeate	$C_{24}H_{30}O_4$	
264	Isobazzanenol	$C_{15}H_{24}O$	
265	Bazzanone A (= 2-Oxobazzanene)	$C_{15}H_{22}O$	

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\text{10}^{-1}$	Plant source(s)	Reference(s)	Comments
266	Bazzanenone B	$\text{C}_{15}\text{H}_{22}\text{O}_2$	108-110	+55.0	Unidentified <i>Frullania</i> sp.	(72)	
267	Bazzanenone C	$\text{C}_{15}\text{H}_{20}\text{O}_2$		+73.8	<i>Frullania squarrosula</i> Unidentified <i>Frullania</i> sp.	(616) (84) (72) (616)	
268	Bazzanenone D	$\text{C}_{15}\text{H}_{20}\text{O}_2$	104-105	-48.0	<i>Frullania squarrosula</i> Unidentified <i>Frullania</i> sp.	(84) (72)	
269	Bazzanenoxide	$\text{C}_{15}\text{H}_{22}\text{O}_2$			<i>Frullania falciloba</i>	(616)	
270	β -Bazzanen-11 α -ol	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Frullania squarrosula</i>	(613)	
271	Bazzanenone E	$\text{C}_{15}\text{H}_{20}\text{O}_2$			<i>Frullania squarrosula</i>	(84)	
272	<i>cis</i> - α -Bergamotene	$\text{C}_{15}\text{H}_{24}$			<i>Calypogeia fissa</i>	(931)	
273	(+)- <i>cis</i> - α -Bergamotene <i>trans</i> - α -Bergamotene	$\text{C}_{15}\text{H}_{24}$ $\text{C}_{15}\text{H}_{24}$			<i>Marsipella alpina</i> <i>Dumortiera hirsuta</i> <i>Barbilophozia floerkei</i> <i>Plagiochila maderensis</i> <i>Plagiochila stricta</i> <i>Radula complanata</i> <i>Radula lindenbergiana</i> <i>Radula wichurae</i> <i>Dumortiera hirsuta</i> <i>Marsipella emarginata</i> <i>Frullania pycnantha</i> <i>Gackstroemia decipiens</i>	(17) (707) (15) (221) (221) (223) (223) (223) (707) (17) (78) (252)	
274	(+)- <i>trans</i> - α -Bergamotene <i>trans</i> - β -Bergamotene	$\text{C}_{15}\text{H}_{24}$ $\text{C}_{15}\text{H}_{24}$					
275	(-)-13-Hydroxybergamota-2,11-diene	$\text{C}_{15}\text{H}_{24}\text{O}$		-49			

276	Clavigerin A	$C_{19}H_{24}O_6$		<i>Lepidolaena clavigera</i>	(72) (616)
277	Clavigerin B	$C_{17}H_{22}O_4$		<i>Lepidolaena clavigera</i>	(657) (656)
278	Clavigerin C	$C_{17}H_{24}O_4$	+15	<i>Lepidolaena clavigera</i>	(657) (656)
279	Methoxy clavigerin B	$C_{16}H_{22}O_3$	−16	<i>Lepidolaena clavigera</i>	(657)
280	Ethoxy clavigerin B	$C_{17}H_{24}O_3$		<i>Lepidolaena clavigera</i>	(657)
281	Methoxy clavigerin C	$C_{16}H_{24}O_3$	+6	<i>Lepidolaena clavigera</i>	(657)
282	δ-Elemene	$C_{13}H_{24}$		<i>Anastrophyllum auritum</i>	(976)
				<i>Archilejeunea scutellata</i>	(72)
				<i>Chandonantus hirtellus</i>	(224)
				<i>Chiloscyphus triacanthus</i>	(72)
				<i>Frullania probosciphora</i>	(78)
				<i>Lepidozia concinna</i>	(72)
				<i>Lepidozia fauriana</i>	(645)
				<i>Lepidozia reptans</i>	(681)
				<i>Lepidozia vitrea</i>	(645)
				<i>Lophozia ventricosa</i>	(486)
				<i>Lunularia cruciata</i>	(72)
				<i>Plagiochasma pterospermum</i>	(314)
				<i>Plagiochila bifaria</i>	(221)
				<i>Plagiochila retrorsa</i>	(221)
				<i>Plagiochila stricta</i>	(221)
				<i>Plagiochila suborbiculata</i>	(72)
				<i>Preissia quadrata</i>	(74)
				<i>Thysananthus anguiformis</i>	(72)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2 \text{ g}^{-1} 10^{-1}$	Plant source(s)	Reference(s)	Comments
283	β -Elenene	$\text{C}_{13}\text{H}_{24}$			<i>Apometzgeria pubescens</i>	(882)	
					<i>Bazzania spiralis</i>	(490)	
					<i>Calypogea muelleriana</i>	(933)	
					<i>Conocephalum conicum</i>	(492)	
					<i>Diplophyllum albicans</i>	(15)	
					<i>Drepanolejeunea</i>	(247)	
					<i>madagascariensis</i>		
					<i>Dumortiera hirsuta</i>	(492)	
					<i>Frullania aterrima</i> var. <i>lepida</i>	(78)	
					<i>Frullania congesta</i>	(78)	
					<i>Frullania falciloba</i>	(78)	
					<i>Frullania fugax</i>	(78)	
					<i>Frullania incumbens</i>	(78)	
					<i>Frullania lobulata</i>	(78)	
					<i>Frullania magellanica</i>	(78)	
					<i>Frullania media</i>	(78)	
					<i>Frullania monocera</i>	(78)	
					<i>Frullania psychantha</i>	(78)	
					<i>Frullania serrata</i>	(490)	
					<i>Frullania tamarisci</i> subsp. <i>obscura</i>	(492)	
					<i>Gymnocolea inflata</i>	(882)	
					<i>Herbertus sakuraii</i>	(323)	
					<i>Heteroscyphus aselliformis</i>	(490)	
					<i>Lejeunea parva</i>	(882)	
					<i>Lepidozia fauriana</i>	(645)	
					<i>Lepidozia vitrea</i>	(645)	

		<i>Lunularia cruciata</i>	(79)
		<i>Marchantia paleacea</i> var. <i>diptera</i>	(492)
		<i>Marsipella aquatica</i>	(877)
			(17)
			(19)
		<i>Mylia taylorii</i>	(922)
		<i>Mylia nuda</i>	(922)
		<i>Plagiiochasma pterospermum</i>	(314)
		<i>Plagiiochila bifaria</i>	(221)
		<i>Plagiiochila retrorsa</i>	(221)
		<i>Plagiiochila stricta</i>	(221)
		<i>Porella acutifolia</i> subsp. <i>tosana</i>	(322)
		<i>Porella grandiloba</i>	(814)
		<i>Porella perrottetiana</i>	(424)
		<i>Radula nudicaulis</i>	(223)
		<i>Radula perrottetii</i>	(826)
		<i>Riccardia nagasakiensis</i>	(141)
		<i>Riccardia palmata</i>	(882)
		<i>Saccogyna viticulosa</i>	(276)
		<i>Tritomaria polita</i>	(18)
		<i>Tritomaria quinqueidentata</i>	(928)
		<i>Frullania fragilifolia</i>	(644)
		<i>Frullania tamarisci</i>	(644)
		<i>Lepidozia reptans</i>	(681)
		<i>Trichocolea pluma</i>	(494)
		<i>Scapania undulata</i>	(16)
		<i>Saccogyna viticulosa</i>	(276)
		<i>Frullania scandens</i>	(78)
		<i>Lejeunea parva</i>	(882)
		<i>Riccardia palmata</i>	(882)
284	(-)- β -Elemene	$C_{15}H_{24}$	
	<i>cis</i> - β -Elemene	$C_{15}H_{24}$	
	(-)- <i>cis</i> - β -Elemene	$C_{15}H_{24}$	
285	(-)- <i>iso</i> - β -Elemene	$C_{15}H_{24}$	
286	Elemene-1,3,7(11),8-tetraene	$C_{15}H_{22}$	
287	Elemol	$C_{15}H_{26}O$	

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
288	(+)-Elemen-1,3-dien-7 β -ol	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Lepidozia vitrea</i>	(645)	
289	(+)-7 β -Acetoxylemen-1,3-dien-8 β -ol	$\text{C}_{17}\text{H}_{28}\text{O}_3$			<i>Lepidozia vitrea</i>	(645)	
290	Bicycloelemene	$\text{C}_{15}\text{H}_{24}$			<i>Bazzania trilobata</i>	(930)	
					<i>Calypogeia muelleriana</i>	(933)	
					<i>Cephaloziella recurvifolia</i>	(955)	
					<i>Chandonanthus hirtellus</i>	(423)	
						(494)	
					<i>Dendromastigophora flagellifera</i>	(72)	
					<i>Diplophyllum albicans</i>	(15)	
					<i>Gymnocolea inflata</i>	(882)	
					Unidentified <i>Jungmannia</i> sp.	(494)	
					<i>Pallavicinia subciliata</i>	(882)	
					<i>Plagiochila suborbiculata</i>	(72)	
					Unidentified <i>Plagiochila</i> sp.	(494)	
					<i>Saccogyna viticulosa</i>	(276)	
					<i>Wetsteinia schusterana</i>	(70)	
291	Dehydrosaussurealactone	$\text{C}_{15}\text{H}_{20}\text{O}_2$			<i>Frullania rostrata</i>	(78)	
292	Saussurealactone	$\text{C}_{15}\text{H}_{22}\text{O}_2$			<i>Frullania rostrata</i>	(78)	
293	Bicyclogermacrene	$\text{C}_{15}\text{H}_{24}$			<i>Apometzgeria pubescens</i>	(882)	
					<i>Archilejeunea scutellata</i>	(72)	
					<i>Barbilophozia floerkei</i>	(15)	
					<i>Bazzania involuta</i>	(72)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Calypogeia fissia</i>	(931)	
					<i>Calypogeia suecia</i>	(934)	
					<i>Cephaloziella recurvifolia</i>	(955)	

<i>Chandonanthus hirtellus</i>	(224)
	(423)
	(494)
<i>Chiloscyphus allodontus</i>	(72)
<i>Chiloscyphus coclitus</i>	(72)
<i>Chiloscyphus triacanthus</i>	(72)
<i>Conocephalum conicum</i>	(492)
<i>Cuspidatula monodon</i>	(72)
	(616)
<i>Dendromastigophora</i>	(72)
<i>flagelifera</i>	
<i>Diplophyllum albicans</i>	(15)
<i>Drepanolejeunea</i>	(247)
<i>madagascariensis</i>	
<i>Frullania aterrima</i> var.	(78)
<i>aterrima</i>	
<i>Frullania aterrima</i> var.	(78)
<i>lepida</i>	
<i>Frullania fragitifolia</i>	(644)
<i>Frullania incumbens</i>	(72)
	(78)
<i>Frullania media</i>	(78)
<i>Frullania monocera</i>	(78)
<i>Frullania solanderiana</i>	(78)
<i>Frullania spinifera</i>	(78)
<i>Frullania tamarisci</i> subsp.	(492)
<i>obscura</i>	
<i>Frullania truncata</i>	(78)
<i>Gymnocolea inflata</i>	(882)
<i>Hymenophyton flabellatum</i>	(72)
<i>Isotachis aubertii</i>	(288)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
					<i>Isotachis lyalli</i>	(73)	
					<i>Isotachis montana</i>	(73)	
					<i>Jamesoniella autumnalis</i>	(109)	
					<i>Jamesoniella tasmanica</i>	(72)	
					Unidentified <i>Jungermannia</i> sp.	(494)	
					<i>Kurzia makinoana</i>	(882)	
					<i>Lepidolaena clavigera</i>	(72)	
					<i>Lepidozia concinna</i>	(72)	
					<i>Makinoa crispata</i>	(492)	
					<i>Marchantia pileata</i>	(72)	
					<i>Marchesinia brachiata</i>	(594)	
					<i>Noteroclada confluens</i>	(492)	
					<i>Odontoschisma denudatum</i>	(882)	
					<i>Pallavicinia subciliata</i>	(882)	
					<i>Pellia endiviifolia</i>	(492)	
					<i>Plagiochila atlantica</i>	(691)	
					<i>Plagiochila bifaria</i>	(221)	
						(277)	
						(333)	
					<i>Plagiochila buchtiniana</i>	(330)	
					<i>Plagiochila carringtonii</i>	(697)	
					<i>Plagiochila circinalis</i>	(72)	
					<i>Plagiochila diversifolia</i>	(330)	
					<i>Plagiochila fasciculata</i>	(72)	
					<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila porelloides</i>	(762)	
					<i>Plagiochila retrorsa</i>	(221)	
						(698)	

<i>Plagiochila rutilans</i>	(693)
<i>Plagiochila sciophila</i>	(492)
<i>Plagiochila standleyi</i>	(693)
<i>Plagiochila stricta</i>	(221)
	(699)
<i>Plagiochila suborbiculata</i>	(72)
<i>Plagiochila yokogurensis</i>	(84)
Unidentified <i>Plagiochila</i> sp.	(494)
	(701)
<i>Porella perrattetiana</i>	(424)
<i>Porella acutifolia</i> subsp. <i>tosana</i>	(322)
<i>Preissia quadrata</i>	(74)
<i>Ptilidium ciliare</i>	(596)
<i>Riccardia palmata</i>	(882)
<i>Saccogyna viticulosa</i>	(276)
<i>Symphyogyna brasiliensis</i>	(492)
<i>Thysananthus anguiformis</i>	(72)
<i>Trichocolea lanata</i>	(72)
<i>Trichocolea mollissima</i>	(72)
<i>Tritomaria quinqueidentata</i>	(928)
<i>Trocholejeunea sandvicensis</i>	(491)
<i>Wetsteinia schusterana</i>	(70)
<i>Anastrophyllum auritum</i>	(976)
<i>Calypogeia muelleriana</i>	(933)
<i>Conocephalum conicum</i>	(543)
<i>Lepidozia fauriana</i>	(645)
<i>Lepidozia reptans</i>	(681)
<i>Leptosciaphus jackii</i>	(893)
<i>Mylia nuda</i>	(922)

(-)-Bicyclogermacrene

C₁₅H₂₄

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
					<i>Mylia taylorii</i>	(922)	
294	Isobicyclogermacrene	$\text{C}_{15}\text{H}_{24}$			<i>Plagiochila asplenoides</i>	(14)	
					<i>Frullania atterrma</i> var. <i>lepida</i>	(78)	
					<i>Frullania patula</i>	(78)	
					<i>Scapania undulata</i>	(16)	
295	Bicyclogermacren-14-al	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Conocephalum conicum</i>	(492)	
						(543)	
					<i>Conocephalum japonicum</i>	(492)	
296	(-)-Bicyclogermacrenal	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Conocephalum conicum</i>	(880)	
297	Isobicyclogermacrenal	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Bazzania decrescens</i>	(291)	
					<i>Chiloscyphus setigera</i>	(347)	
					<i>Lepidozia vitrea</i>	(871)	
298	(-)-Isobicyclogermacrenal	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Barbilophozia floerkei</i>	(15)	
	3 α -Acetoxybicyclogermacrene	$\text{C}_{17}\text{H}_{26}\text{O}_2$			<i>Cephalozia recurvifolia</i>	(955)	
					<i>Diplophyllum albicans</i>	(15)	
					<i>Jamesoniella autumnalis</i>	(109)	
					<i>Lepidozia spinosissima</i>	(611)	
					<i>Plagiochila asplenoides</i>	(14)	
					<i>Plagiochila cristata</i>	(911)	
					<i>Plagiochila diversifolia</i>	(330)	
					<i>Plagiochila ericicola</i>	(911)	
					<i>Plagiochila yokogurensis</i>	(84)	
299	(+)- <i>cis</i> -3 β -Acetoxybicyclogermacra- [1(10) <i>E</i> ,4 <i>E</i>]-diene	$\text{C}_{17}\text{H}_{26}\text{O}_2$		+28	<i>Chandonanthus hirtellus</i>	(927)	
300	<i>ent</i> -3 β -Acetoxy-2 β -hydroxy- bicyclogermacrene	$\text{C}_{17}\text{H}_{26}\text{O}_3$		+69.3	<i>Heteroscyphus planus</i>	(562)	Cell culture

301	3 α ,14-Diacetoxy-2 α -hydroxy-bicyclogermacrene	C ₁₉ H ₂₈ O ₅	<i>Plagiochila ovalifolia</i>	(84)
302	2 α ,3 α -Diacetoxy-14-hydroxy-bicyclogermacrene	C ₁₉ H ₂₈ O ₅	<i>Plagiochila yokogurensis</i>	(84)
303	Atlanticol [(1R*, 2R*, 3R*, 4E, 6S*, 7S*, 10S*)-3,14-diacetoxy-1,10-epoxy-bicyclogermacr-4-en-2-ol]	C ₁₉ H ₂₈ O ₆	<i>Plagiochila aerea</i>	(334)
			<i>Plagiochila atlantica</i>	(691)
304	Atlanticol acetate	C ₂₁ H ₃₀ O ₇	<i>Plagiochila aerea</i>	(334)
305	(1R*, 2R*, 3S*, 5S*, 6R*, 7S*, 10S*)-2,3,14-triacetoxy-1,10-epoxy-bicyclogermacr-4(15)-en-5-ol	C ₂₁ H ₃₀ O ₈	<i>Plagiochila atlantica</i>	(691)
306	(+)-3 α -Acetoxy-2 α -[3-(4-hydroxy-3-methoxyphenyl)-propanoyloxy] bicyclogermacr-(E)1(10),4(12)-dien-5 β -ol	C ₂₇ H ₃₆ O ₇	<i>Plagiochila eritricola</i>	(911)
		+24.8		
307	Isolepidozene	C ₁₅ H ₂₄	<i>Conocephalum conicum</i>	(492)
			<i>Conocephalum japonicum</i>	(492)
			<i>Cyathodium foetidissimum</i>	(494)
			<i>Marchantia tosaana</i>	(492)
			<i>Conocephalum conicum</i>	(543)
			<i>Frullania tamarisci</i>	(286)
			<i>Scapania aequiloba</i>	(286)
			<i>Preissia quadrata</i>	(286)
308	Lepidozenal	C ₁₅ H ₂₂ O	<i>Bazzania tricenata</i>	(84)
			<i>Lepidozia reptans</i>	(681)
			<i>Lophozia ventricosa</i>	(486)
	(-)-Lepidozenal	C ₁₅ H ₂₂ O	<i>Lepidozia fauriana</i>	(645)
			<i>Lepidozia vitrea</i>	(645)
				(871)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
309	(4S*,5S*,6R*,7R*)-(1(10)E)-lepidozen-5-ol	C ₁₅ H ₂₆ O			<i>Dumortiera hirsuta</i>	(876)	
					<i>Marchantia tosona</i>	(492)	
					<i>Porella swartziana</i>	(848)	
310	(4S*,5S*,6R*,7R*)-5-Methoxy-(1(10)E)-lepidozene	C ₁₆ H ₂₈ O		-75.2	<i>Porella subobtusata</i>	(569)	
311	Lepidozenol	C ₁₅ H ₂₄ O			<i>Bryopteris filicina</i>	(604)	
312	Lepidoza-1(10),4(14)-dien-5-ol	C ₁₅ H ₂₄ O			<i>Bryopteris filicina</i>	(604)	
313	α -Bisabolene	C ₁₅ H ₂₄			<i>Jamesoniella autumnalis</i>	(109)	
	(Z)- α -Bisabolene	C ₁₅ H ₂₄			<i>Frullania deplanata</i>	(78)	
314	(E)- α -Bisabolene	C ₁₅ H ₂₄			<i>Scapania undulata</i>	(16)	
315	β -Bisabolene	C ₁₅ H ₂₄			<i>Barbilophozia floerkei</i>	(15)	
					<i>Calyptopogon fissa</i>	(931)	
					<i>Frullania deplanata</i>	(78)	
					<i>Frullania probosciphora</i>	(78)	
					<i>Gymnocolea inflata</i>	(882)	
					<i>Jamesoniella autumnalis</i>	(109)	
					<i>Metacalyptopogon alternifolia</i>	(748)	
					<i>Metacalyptopogon cordifolia</i>	(882)	
						(894)	
					<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Porella navicularis</i>	(143)	Cell culture
					<i>Porella vernicosa</i>	(637)	
					<i>Radula aquilegia</i>	(223)	
					<i>Radula boryana</i>	(224)	
					<i>Radula complanata</i>	(223)	
					<i>Radula holzii</i>	(223)	

316	(Z)- γ -Bisabolene	C ₁₅ H ₂₄	<i>Radula lindenbergiana</i> (223) <i>Radula nudicaulis</i> (223) <i>Radula wichurae</i> (223) <i>Wetssteinia schusterana</i> (70) <i>Calypogeia suecia</i> (934) <i>Dumortiera hirsuta</i> (707) <i>Radula complanata</i> (223) <i>Radula holtii</i> (223) <i>Radula lindenbergiana</i> (223) <i>Radula nudicaulis</i> (223) <i>Radula perrottetii</i> (826) <i>Radula perrottetii</i> (492) (826) <i>Chandonanthus hirrellus</i> (927) <i>Calypogeia sueciai</i> (934) Unidentified <i>Frullania</i> sp. (424) <i>Mannia fragrans</i> (542) <i>Marchantia chenopoda</i> (841) <i>Bazzania tridens</i> (959) <i>Plagiochila asplenoides</i> (14) <i>Plagiochila asplenoides</i> (14) <i>Radula perrottetii</i> (826) <i>Radula holtii</i> (223) <i>Radula perrottetii</i> (826) <i>Radula perrottetii</i> (826) <i>Radula perrottetii</i> (826) <i>Bazzania tridens</i> (959) <i>Marchantia foliacea</i> (347) <i>Bazzania tridens</i> (959)
317	(E)- γ -Bisabolene	C ₁₅ H ₂₄	
	Bisabola-2,6,11-triene	C ₁₅ H ₂₄	
318			
319	(-)-(6R,7S)-Sesquiphellandrene	C ₁₅ H ₂₄	
320	(-)-(6S)- β -Sesquiphellandrene	C ₁₅ H ₂₄	
321			
	Bisabola-1,3,5,7(14)-tetraene	C ₁₅ H ₂₂	
322	Bisabola-1,3,5,7-tetraene	C ₁₅ H ₂₂	
323	Bisabola-1,3,5,7(14),11-pentaene	C ₁₅ H ₂₀	
324	Bisabola-1,3,5,7(14),10-pentaene	C ₁₅ H ₂₀	
325			
	Bisabola-1,3,5,7,11-pentaene	C ₁₅ H ₂₀	
326	6,7-Epoxybisabola-2,11-diene	C ₁₅ H ₂₄ O	
327	1,3,5-Bisabolatrien-7-ol	C ₁₅ H ₂₄ O	
328	1,3,5-Bisabolatrien-7 α -ol	C ₁₅ H ₂₄ O	
329	14- <i>nor</i> -1,3,5-Bisabolatrien-7-one	C ₁₄ H ₂₀ O	

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ °cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
330	(4S,6R)-2,7,10-Bisabolatrien-4-ol	C ₁₅ H ₂₄ O		-9.7	<i>Dumortiera hirsuta</i>	(876)	
331	(+)-(6R,7R)- α -Bisabolol	C ₁₅ H ₂₆ O			<i>Pellia epiphylla</i>	(176)	
332	(+)-Bisabola-2,10-diene(1,9)oxide	C ₁₅ H ₂₄ O			<i>Calypogeia suecica</i>	(934)	
333	<i>arr</i> -Curcumene	C ₁₅ H ₂₂			<i>Calypogeia fissa</i>	(931)	
					<i>Dumortiera hirsuta</i>	(490)	
						(707)	
					<i>Scapania undulata</i>	(16)	
	(-)- <i>arr</i> -Curcumene	C ₁₅ H ₂₂			<i>Anastrophyllum auritum</i>	(976)	
	(+)- <i>arr</i> -Curcumene	C ₁₅ H ₂₂			<i>Calypogeia suecica</i>	(934)	
334	β -Curcumene	C ₁₅ H ₂₄			<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Radula lindenbergiana</i>	(223)	
					<i>Radula wichurae</i>	(223)	
335	γ -Curcumene	C ₁₅ H ₂₄			<i>Calypogeia fissa</i>	(931)	
					<i>Plagiochila asplenoides</i>	(14)	
	(+)- γ -Curcumene	C ₁₅ H ₂₄			<i>Calypogeia suecica</i>	(934)	
336	β -Bourbonene	C ₁₅ H ₂₄			<i>Drepanolejeunea</i> <i>madagascariensis</i>	(247)	
					Unidentified <i>Jungmannia</i> sp.	(494)	
					<i>Lepidozia borneensis</i>	(490)	
						(645)	
					<i>Lepidozia vitrea</i>	(220)	
					<i>Marchesinia mackatii</i>	(221)	
					<i>Plagiochila bifaria</i>	(277)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
	(+)- β -Bourbonene	C ₁₅ H ₂₄			<i>Lepidozia reptans</i>	(681)	

337	Bourbon-11-ene	C ₁₅ H ₂₄	Unidentified <i>Jungmannia</i> sp. <i>Kurzia trichoclados</i> <i>Mylia taylorii</i> <i>Mylia nuda</i> <i>Pellia endiviifolia</i> <i>Calyptogea muelleriana</i> <i>Frullania tamarisci</i> <i>Frullania fragilifolia</i> <i>Tritomaria quinqueidentata</i> <i>Symphogyna brasiliensis</i> <i>Kurzia trichoclados</i> <i>Mylia nuda</i> <i>Mylia taylorii</i> <i>Phycanthus striatus</i> <i>Conocephalum conicum</i> <i>Conocephalum conicum</i> <i>Notoclada confluens</i> <i>Conocephalum conicum</i> <i>Notoclada confluens</i> <i>Conocephalum conicum</i> <i>Apometzgeria pubescens</i> <i>Bryopteris flicina</i> <i>Calyptogea muelleriana</i> <i>Frullania anomala</i> <i>Frullania aterrima</i> var. <i>lepidia</i> <i>Frullania congesta</i> <i>Frullania incumbens</i> <i>Frullania ptychantha</i>	(494) (922) (922) (922) (492) (933) (644) (644) (928) (492) (922) (922) (922) (396) (543) (543) (492) (543) (492) (493) (841) (882) (604) (933) (78) (78) (78) (78) (78) (78) (78) (78)	Cell culture
338	Bourbon-7(11)-ene	C ₁₅ H ₂₄			
339	(-)-(1S*,5S*,6S*,7S*,10S*)-7-epi-Bourbon-3-en-5,11-oxide	C ₁₅ H ₂₄ C ₁₅ H ₂₂ O			
340	Prespatane	C ₁₅ H ₂₄			
341	Brasil-5,10-diene	C ₁₅ H ₂₄			
342	Brasil-5(10),6-diene	C ₁₅ H ₂₄			
343	Brasil-1(6),5(10)-diene	C ₁₅ H ₂₄			
344	Brasil-1,10-diene	C ₁₅ H ₂₄			
345	Conocephalenol	C ₁₅ H ₂₄ O			
346	γ-Cadinene	C ₁₅ H ₂₄			

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
347	δ -Cadinene	$\text{C}_{15}\text{H}_{24}$			<i>Isotachis aubertii</i>	(288)	
					Unidentified <i>Jungmannia</i> sp.	(494)	
					<i>Lepidozia concinna</i>	(72)	
					<i>Marchantia foliacea</i>	(72)	
					<i>Marchantia pileata</i>	(72)	
					<i>Paraschistochila tuloides</i>	(72)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Riccardia nagasakiensis</i>	(141)	
					<i>Drepanolejeunea</i>	(247)	
					<i>madagascariensis</i>		
					<i>Lepidozia vitrea</i>	(645)	
					<i>Lophozia ventricosa</i>	(486)	
					<i>Marchesinia mackaii</i>	(220)	
348	(–)- δ -Cadinene	$\text{C}_{15}\text{H}_{24}$ $\text{C}_{15}\text{H}_{24}$			<i>Marsupella emarginata</i>	(17)	
					<i>Plagiochila bifaria</i>	(221)	
					<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
349	Cadina-1,4-diene	$\text{C}_{15}\text{H}_{24}$			<i>Radula carringtonii</i>	(223)	
					<i>Scapania undulata</i>	(16)	
					<i>Preissia quadrata</i>	(433)	
350	Cadina-3,5-diene	$\text{C}_{15}\text{H}_{24}$			<i>Calypogeia muelleriana</i>	(933)	
					<i>Marchantia emarginata</i> subsp. <i>tosana</i>	(347)	
349	Cadina-1,4-diene	$\text{C}_{15}\text{H}_{24}$			<i>Calypogeia muelleriana</i>	(933)	
					<i>Marsupella aquatica</i>	(19)	
350	Cadina-3,5-diene	$\text{C}_{15}\text{H}_{24}$			Unidentified <i>Pallavicinia</i> sp.	(490)	

351	Bicyclosesquiphellandrene	C ₁₅ H ₂₄	Unidentified <i>Pallavicinia</i> sp.	(490)
352	(-)- <i>cis</i> -Cadina-1(6),4-diene	C ₁₅ H ₂₄	<i>Bazzania trilobata</i>	(930)
353	T-Cadinol	C ₁₅ H ₂₆ O	<i>Calypogeia muelleriana</i>	(933)
			<i>Frullania tamarisci</i>	(644)
			<i>Plagiochila bifaria</i>	(221)
			<i>Plagiochila retrorsa</i>	(221)
354	α -Cadinol	C ₁₅ H ₂₆ O	Unidentified <i>Jungmannia</i> sp.	(494)
			<i>Plagiochila bifaria</i>	(221)
			<i>Plagiochila retrorsa</i>	(221)
355	(-)- α -Cadinol	C ₁₅ H ₂₆ O	<i>Calypogeia muelleriana</i>	(933)
356	(+)- α -Cadinol	C ₁₅ H ₂₆ O	<i>Jackiella javanica</i>	(608)
	δ -Cadinol	C ₁₅ H ₂₆ O	<i>Plagiochila bifaria</i>	(221)
			<i>Plagiochila retrorsa</i>	(221)
357	Cubenol	C ₁₅ H ₂₆ O	<i>Bazzania japonica</i>	(485)
358	1- <i>epi</i> -Cubenol	C ₁₅ H ₂₆ O	<i>Scapania undulata</i>	(16)
	(+)-1- <i>epi</i> -Cubenol	C ₁₅ H ₂₆ O	<i>Marsupella aquatica</i>	(19)
			<i>Scapania undulata</i>	(569)
359	Cadina-4,11-dien-14-al	C ₁₅ H ₂₂ O	<i>Reboulia hemisphaerica</i>	(577)
360	Cadina-4,11-dien-14-ol	C ₁₅ H ₂₄ O	<i>Reboulia hemisphaerica</i>	(935)
361	14-Acetoxycadina-4,11-diene	C ₁₇ H ₂₆ O ₂	<i>Reboulia hemisphaerica</i>	(935)
362	Cadina-4,11-dien-14-oic acid (= Parnetic acid)	C ₁₅ H ₂₂ O ₂	<i>Reboulia hemisphaerica</i>	(935)
363	7,10-Peroxycadina-5-ene	C ₁₅ H ₂₄ O ₂	<i>Bazzania trilobata</i>	(582)
364	Rupestrenol [(+)- (1 <i>R</i> *,6 <i>S</i> *,7 <i>S</i> *,10 <i>S</i> *)- 12-Hydroxy-4,11(13)- cadinadiene]	C ₁₅ H ₂₄ O	<i>Plagiochasma rupestre</i>	(97)
		50-52		X-ray
365	5,11-Epoxycadin-10 α -ol	C ₁₅ H ₂₆ O ₂	<i>Phycanthus striatus</i>	(325)
366	Secoinfufucanal	C ₁₅ H ₂₄ O ₂	<i>Jungmannia infusca</i>	(600)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2 \text{ g}^{-1} 10^{-1}$	Plant source(s)	Reference(s)	Comments
367	α -Amorphene	$\text{C}_{15}\text{H}_{24}$			<i>Lepidozia fauriana</i> <i>Metacalypogeia alternifolia</i> <i>Tritomaria polita</i>	(645) (748) (18)	
368	(+)- α -Amorphene (-)- γ -Amorphene	$\text{C}_{15}\text{H}_{24}$ $\text{C}_{15}\text{H}_{24}$			<i>Scapania undulata</i> Unidentified <i>Frullania</i> sp.	(16) (424)	
369	δ -Amorphene	$\text{C}_{15}\text{H}_{24}$			<i>Preissia quadrata</i> <i>Frullania spinifera</i>	(433) (78)	
370	(+)-Amorpha-4,11-diene	$\text{C}_{15}\text{H}_{24}$			<i>Tritomaria polita</i> <i>Marsupella aquatica</i>	(18) (17)	
371	(-)-Amorpha-4,7(11)-diene	$\text{C}_{15}\text{H}_{24}$			<i>Marsupella aquatica</i>	(19) (17)	
372	(-)-2-Acetoxyamorpha-4,7(11)-diene	$\text{C}_{17}\text{H}_{26}\text{O}_2$			<i>Marsupella aquatica</i>	(19) (17)	
373	(-)-(1R,2S,6R,10S)-2 α -Acetoxy-amorpha-4,7(11)-dien-8-one	$\text{C}_{17}\text{H}_{24}\text{O}_3$		-155.1	<i>Marsupella emarginata</i> var. <i>aquatica</i>	(465)	
374	(-)-(1R,2S,6R,10S)-2 α -Acetoxy-11-methoxyamorpha-4,7-diene	$\text{C}_{18}\text{H}_{28}\text{O}_3$		-36.9	<i>Marsupella emarginata</i> var. <i>aquatica</i>	(465)	
375	(-)-(1R,2R,3S,6R,10S)-2 α ,3 α -Diacetoxyamorpha-4,7(11)-dien-8-one	$\text{C}_{19}\text{H}_{26}\text{O}_5$		-93.8	<i>Marsupella emarginata</i> var. <i>aquatica</i>	(465)	
376	(-)-(1R,2R,3R,6R,9S,10R)-2 α ,3 α -Diacetoxy-9 α -hydroxyamorpha-4,7(11)-dien-8-one	$\text{C}_{19}\text{H}_{26}\text{O}_6$	126-127	-117.0	<i>Marsupella emarginata</i> var. <i>aquatica</i>	(465)	
377	(+)-(1R,6S,10S)-7 β -Hydroxy-amorpha-4,11-diene	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Marsupella aquatica</i>	(19)	
378	(+)-(1R,2S,6R,8S,10S)-2,8-Epoxy-amorpha-4,7(11)-diene	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Marsupella aquatica</i>	(19)	
379	(+)-(1S,5S,6R,9R,10R)-5,9-Epoxy-amorpha-3,7(11)-diene	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Marsupella aquatica</i>	(19)	

380	(-)-(1S,6S,9R,10R)-9 α -Hydroxy-amorpha-4,7(11)-diene	C ₁₅ H ₂₄ O	<i>Marsupella aquatica</i>	(19)
381	(-)-(1R,6S,9R,10R)-3 α -Hydroxy-amorpha-4,7(11)-diene	C ₁₅ H ₂₄ O	<i>Marsupella aquatica</i>	(19)
382	(-)-(1R,3R,6S,10S)-3 α -Acetoxy-amorpha-4,7(11)-diene	C ₁₇ H ₂₆ O ₂	<i>Marsupella aquatica</i>	(19)
383	(-)-(1R,6S,10S)-Amorpha-4,7(11)-dien-3-one	C ₁₅ H ₂₂ O	<i>Marsupella aquatica</i>	(19)
384	(-)-(1R,2S,6R,10S)-2 α -Hydroxy-amorpha-4,7(11)-diene	C ₁₅ H ₂₄ O	<i>Marsupella aquatica</i>	(19)
385	(-)-(1R,2S,6R,10S)-2 β -Acetoxy-amorpha-4,7(11)-diene	C ₁₇ H ₂₆ O ₂	<i>Marsupella aquatica</i>	(19)
386	(+)-Amorpha-4,9-dien-2 α -ol	C ₁₅ H ₂₄ O	<i>Lepidozia fauriana</i>	(645)
387	(+)-Amorpha-4,9-dien-14-al	C ₁₅ H ₂₂ O	<i>Lepidozia fauriana</i>	(645)
388	(+)-7,14-Anhydroamorpha-4,9-diene	C ₁₅ H ₂₂ O	<i>Lepidozia fauriana</i>	(645)
389	(+)-Lepidozenolide	C ₁₅ H ₂₀ O ₂	<i>Lepidozia fauriana</i>	(746)
390	(-)-5 β -Hydroperoxylepidozenolide	C ₁₅ H ₂₀ O ₄	<i>Lepidozia fauriana</i>	(747)
391	4,9-Amorphadien-8-one	C ₁₅ H ₂₂ O	<i>Lepidozia vitrea</i>	(746)
392	α -Murolene	C ₁₅ H ₂₄	<i>Lepidozia setigera</i>	(347)
			<i>Bazzania japonica</i>	(485)
			Unidentified <i>Frullania</i> sp.	(424)
			<i>Marchesinia mackaii</i>	(220)
			<i>Marsupella emarginata</i>	(17)
			<i>Porella navicularis</i>	(143)
			<i>Plagiochila retrorsa</i>	(221)
393	γ -Murolene	C ₁₅ H ₂₄	<i>Dumortiera hirsuta</i>	(492)
			<i>Frullania fragilifolia</i>	(644)
394	ϵ -Murolene	C ₁₅ H ₂₄	<i>Marchesinia mackaii</i>	(220)
395	<i>cis</i> -Murola-4(15),5-diene	C ₁₅ H ₂₄	Unidentified <i>Jungermannia</i> sp.	(494)
			Unidentified <i>Jungermannia</i> sp.	(494)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
396	T-Muurolol	C ₁₅ H ₂₆ O			<i>Calypogeia muelleriana</i>	(933)	
	<i>ent</i> -T-Muurolol	C ₁₅ H ₂₆ O			Unidentified <i>Jungmannia</i> sp.	(494)	
397	(+)-10β <i>H</i> -Muurola-3,7(11)-dien-1-ol	C ₁₅ H ₂₄ O			<i>Scapania undulata</i>	(569)	
397c	Zonarene	C ₁₅ H ₂₄			<i>Calypogeia fissa</i>	(931)	
398	Scapanol	C ₁₅ H ₂₆ O		+5.8	<i>Mastigophora dictados</i>	(425)	
399	(+)-4-Muurolen-6α-ol	C ₁₅ H ₂₆ O		+16.0	<i>Scapania undulata</i>	(577)	
400	1,4-Peroxy-5-muurolene	C ₁₅ H ₂₄ O ₂		+41.9	<i>Scapania undulata</i>	(569)	
401	(+)-Muurolan-4,7-peroxide	C ₁₅ H ₂₆ O ₂			<i>Plagiophila asplenoides</i>	(14)	
402	(1 <i>R</i> *,4 <i>R</i> *,6 <i>R</i> *,10 <i>S</i> *)-Plagio-4,7-peroxide	C ₁₅ H ₂₆ O ₂			<i>Plagiophila asplenoides</i>	(14)	
						(604)	
403	(1 <i>S</i> ,4 <i>S</i>)-Calamenene	C ₁₅ H ₂₂			<i>Plagiophila ovalifolia</i>	(84)	
					<i>Calypogeia muelleriana</i>	(933)	
					<i>Gymnocolea inflata</i>	(882)	
					<i>Kurzia makinoana</i>	(882)	
					<i>Lepidozia concinna</i>	(72)	
					<i>Makinoa crispata</i>	(492)	
					<i>Odontoschisma denudatum</i>	(882)	
					<i>Radula boryana</i>	(224)	
					<i>Radula buccinifera</i>	(72)	
					<i>Trichocolea mollissima</i>	(72)	
					<i>Bazzania trilobata</i>	(582)	
404	(1 <i>R</i> ,4 <i>R</i>)-Calamenene [(+)- <i>cis</i> -Calamenene]	C ₁₅ H ₂₂			Unidentified <i>Frullania</i> sp.	(930)	
					<i>Herbertus sakuraii</i>	(424)	
						(323)	
						(365)	
					<i>Leptolaena hodgsoniae</i>	(101)	

405	<i>trans</i> -Calamenene [(1 <i>S</i> ,4 <i>R</i>)]	C ₁₅ H ₂₂	<i>Bazzania japonica</i> (485)
406	5-Hydroxycalamenene	C ₁₅ H ₂₂ O ₂	<i>Plagiochila retrorsa</i> (221) <i>Bazzania tricrenata</i> (84) <i>Bazzania trilobata</i> (715) <i>Calypogeia muelleriana</i> (933) <i>Frullania spinifera</i> (78) <i>Kurzia makinoana</i> (882) <i>Bazzania trilobata</i> (582) (930)
407	(1 <i>R</i> ,4 <i>R</i>)- <i>cis</i> -5-Hydroxycalamenene	C ₁₅ H ₂₂ O ₂	+33.4 <i>Bazzania tricrenata</i> (84) <i>Bazzania trilobata</i> (715) <i>Dumortiera hirsuta</i> (487) <i>Heteroscyphus codlitus</i> (617) <i>Kurzia makinoana</i> (882) <i>Bazzania nitida</i> (289) <i>Heteroscyphus planus</i> (310) <i>Bazzania trilobata</i> (582) (930)
408	7-Hydroxycalamenene	C ₁₅ H ₂₂ O ₂	+55.4 <i>Heteroscyphus planus</i> (310) <i>Heteroscyphus codlitus</i> (617) <i>Dumortiera hirsuta</i> (487) <i>Chiloscyphus polyanthos</i> (498) <i>Chiloscyphus polyanthos</i> (498) <i>Chiloscyphus polyanthos</i> (498) <i>Bazzania japonica</i> (498)
409	(+)-(1 <i>S</i> ,4 <i>R</i>)-7-Hydroxycalamenene	C ₁₅ H ₂₂ O ₂	+45.6 <i>Bazzania japonica</i> (498)
410	<i>cis</i> -8-Hydroxycalamenene	C ₁₅ H ₂₂ O ₂	+38.2 <i>Bazzania japonica</i> (498)
411	(+)-5,8-Dihydroxycalamenene	C ₁₅ H ₂₂ O ₂	+98.5 <i>Bazzania japonica</i> (498)
412	5,7-Dihydroxycalamenene	C ₁₅ H ₂₂ O ₂	+98.5 <i>Bazzania japonica</i> (498)
413	7-Acetoxy-8-hydroxycalamenene	C ₁₇ H ₂₄ O ₃	
414	Chiloscyphenol A	C ₁₅ H ₂₂ O	
415	Chiloscyphenol B	C ₁₅ H ₂₂ O ₂	
416	Chiloscyphone A	C ₁₅ H ₂₁ O ₃	
417	Bazzaninol A [(1 <i>S</i> *,4 <i>R</i> *)-1,2,3,4-tetrahydro-1,7-dimethyl-4-(1-methylethyl)-6-methoxynaphthalene]	C ₁₆ H ₂₄ O	
418	1,6-Dimethyltetrahydro-naphthalen-4-one (trinorsesquiterpene)	C ₁₂ H ₁₄ O	<i>Jungmannia truncata</i> (569)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
419	α -Calacorene	$\text{C}_{15}\text{H}_{20}$			<i>Bazzania japonica</i>	(485)	
					<i>Bazzania trilobata</i>	(930)	
420	γ -Calacorene	$\text{C}_{15}\text{H}_{20}$			<i>Calypogeia muelleriana</i>	(933)	
					<i>Bazzania trilobata</i>	(930)	
421	Cadalene	$\text{C}_{15}\text{H}_{18}$			<i>Calypogeia muelleriana</i>	(933)	
					<i>Bazzania trilobata</i>	(930)	
422	(+)-(1S,4R)-7-Methoxycalamenene	$\text{C}_{16}\text{H}_{24}\text{O}$			<i>Calypogeia muelleriana</i>	(933)	
423	(-)-(1S)-7-Hydroxydihydrocadalene	$\text{C}_{15}\text{H}_{20}\text{O}$			<i>Heteroscyphus planus</i>	(320)	
424	(-)-(1S)-7-Methoxydihydrocadalene	$\text{C}_{16}\text{H}_{22}\text{O}$			<i>Heteroscyphus planus</i>	(320)	
425	7-Methoxycadalene	$\text{C}_{16}\text{H}_{22}\text{O}$			<i>Heteroscyphus planus</i>	(320)	
426	β -Caryophyllene	$\text{C}_{15}\text{H}_{24}$			<i>Aneura alterniloba</i>	(72)	
					<i>Asterella africana</i>	(222)	
					<i>Asterella echinella</i>	(492)	
					<i>Asterella venosa</i>	(492)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Bryopteris filicina</i>	(604)	
					<i>Cheilejeunea trifaria</i>	(309)	
					<i>Conocephalum conicum</i>	(492)	
					<i>Dumortiera hirsuta</i>	(707)	
					<i>Frullania aterrima</i> var. <i>aterrima</i>	(78)	
					<i>Frullania falciloba</i>	(78)	
					<i>Frullania inflata</i>	(893)	
					<i>Frullania monocera</i>	(78)	
					<i>Frullania probosciphora</i>	(78)	
					<i>Frullania pycnantha</i>	(78)	
					<i>Frullania spinifera</i>	(78)	

	<i>Frullania tamarisci</i> subsp. <i>obscura</i>	(492)
	<i>Hymenophyton flabellatum</i>	(77)
	<i>Kurzia makinoana</i>	(882)
	<i>Lepidozia fauriana</i>	(645)
	<i>Lophozia ventricosa</i>	(220)
	<i>Marchantia paleacea</i> var. <i>diptera</i>	(426) (492)
	<i>Marchesinia mackatii</i>	(877)
	<i>Metzgeria furcata</i>	(486)
	<i>Marchesinia brachiata</i>	(72)
	<i>Plagiochasma pterospermum</i>	(594)
	<i>Plagiochila bifaria</i>	(314)
	<i>Ptilidium ciliare</i>	(221)
	<i>Preissia quadrata</i>	(596)
	<i>Radula carringtonii</i>	(74)
	<i>Reboulia hemisphaerica</i>	(223)
	<i>Scapania undulata</i>	(492)
	<i>Trocholejeunea sandvicensis</i>	(16)
	<i>Bazzania japonica</i>	(492)
	<i>Corsinia coriandrina</i>	(485)
	<i>Metzgeria conjugata</i>	(921)
	<i>Pellia endiviifolia</i>	(230)
	<i>Pellia epiphylla</i>	(230)
	<i>Preissia quadrata</i>	(230)
	<i>Fossombronina alackana</i>	(433)
	<i>Fossombronina pusilla</i>	(230)
	<i>Plagiochasma appendiculatum</i>	(230)
	<i>Ptilidium pulcherrimum</i>	(861) (230)
(+)- β -Caryophyllene	$C_{15}H_{24}$	
(-)- β -Caryophyllene	$C_{15}H_{24}$	

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
					<i>Trichocolea tomentella</i>	(230)	
427	2- <i>epi</i> - β -Caryophyllene	$\text{C}_{15}\text{H}_{24}$			<i>Marsipella emarginata</i>	(17)	
428	β -Caryophylleneoxide	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Asterella africana</i>	(222)	
					<i>Dumortiera hirsuta</i>	(96)	
					<i>Frullania hamatiliba</i>	(316)	
					<i>Frullania probosciphora</i>	(78)	
					<i>Marchantia paleacea</i> var. <i>diptera</i>	(436)	
						(492)	
						(877)	
					<i>Pellia epiphylla</i>	(175)	Sporophyte
					<i>Plagiochasma rupestre</i>	(97)	
	(+)- β -Caryophylleneoxide	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Preissia quadrata</i>	(433)	
	(-)- β -Caryophylleneoxide (= 6,7-Epoxyaryophyllene)	$\text{C}_{15}\text{H}_{24}\text{O}$		-62.6	<i>Fossombronina alaskana</i>	(268)	
				-49.4	<i>Plagiochasma appendiculatum</i>	(861)	
					<i>Bazzania japonica</i>	(485)	
429	Caryolan-1-ol	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Marchantia paleacea</i>	(424)	
429a	Caryophylla-3(15),7(14)-dien-6-ol	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Calypogeia fissa</i>	(931)	
430	α -Cedrene	$\text{C}_{15}\text{H}_{24}$			<i>Chiloscyphus amophilus</i>	(72)	
					<i>Porella navicularis</i>	(143)	
					<i>Radula lindenbergiana</i>	(223)	
					<i>Radula perrottetii</i>	(826)	
					<i>Radula wichurae</i>	(223)	
					<i>Schistochila ciliata</i>	(72)	
					<i>Trocholejeunea sandvicensis</i>	(539)	
431	7- <i>epi</i> - α -Cedrene	$\text{C}_{15}\text{H}_{24}$			<i>Radula aquilegia</i>	(223)	
					<i>Radula boryana</i>	(224)	
					<i>Radula perrottetii</i>	(826)	
					<i>Radula wichurae</i>	(223)	

432	β -Cedrene	$C_{15}H_{24}$		<i>Calypogeia fissa</i>	(931)
				<i>Frullania squarrosula</i>	(78)
				Unidentified <i>Frullania</i> sp.	(424)
				<i>Lepidozia fauriana</i>	(645)
				<i>Porella perrottetiana</i>	(424)
				<i>Radula lindenbergiana</i>	(223)
				<i>Radula wichurae</i>	(223)
				<i>Tritomaria quinqueidentata</i>	(928)
				<i>Porella navicularis</i>	(143)
				<i>Bazzania trilobata</i>	(930)
				<i>Bazzania japonica</i>	(485)
				<i>Marchantia polymorpha</i>	(492)
				<i>Marsupella aquatica</i>	(19)
				<i>Marsupella emarginata</i>	(15)
				<i>Mylia taylorii</i>	(922)
436	(+)- α -Chamigrene β -Chamigrene	$C_{15}H_{24}$ $C_{15}H_{24}$	+89	<i>Plagiochila asplenoides</i>	(14)
				<i>Plagiochila porelloides</i>	(762)
				<i>Radula perrottetii</i>	(492)
					(826)
				<i>Scapania undulata</i>	(16)
				<i>Bazzania japonica</i>	(485)
				<i>Bazzania madagassa</i>	(293)
				<i>Bazzania novae-zealandiae</i>	(72)
				<i>Bazzania trilobata</i>	(930)
				<i>Chiloscyphus lingulatus</i>	(72)
				<i>Frullania incumbens</i>	(72)
				<i>Kurzia trichoclados</i>	(922)
				<i>Lepidozia borneensis</i>	(490)
				<i>Marsupella emarginata</i>	(15)
					(17)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ / ° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
					<i>Mylia taylorii</i>	(922)	
					<i>Omphalanthus fliformis</i>	(844)	
					<i>Plagiochila bifaria</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Plagiochila asplenoides</i>	(14)	
					<i>Plagiochila porolloides</i>	(762)	
					<i>Radula perrottetii</i>	(492)	
						(826)	
					<i>Reboulia hemisphaerica</i>	(492)	
					<i>Marchantia polymorpha</i>	(492)	
437	<i>ent</i> -9-oxo- α -Chamigrene (Laurencenone C)	C ₁₅ H ₂₂ O				(242)	
438	<i>ent</i> - β -Chamigrene-1 α -ol	C ₁₅ H ₂₄ O		+23.7	<i>Reboulia hemisphaerica</i>	(492)	
439	<i>ent</i> - β -Chamigrene-8 β -ol	C ₁₅ H ₂₄ O		-64.4	<i>Reboulia hemisphaerica</i>	(242)	
440	Methyl chamigrenate	C ₁₆ H ₂₄ O ₂		+99.5	<i>Omphalanthus fliformis</i>	(844)	
441	Chamigrenic acid	C ₁₅ H ₂₂ O ₂			<i>Omphalanthus fliformis</i>	(844)	
442	Methyl omphalate	C ₁₆ H ₂₄ O ₂		+74.5	<i>Omphalanthus fliformis</i>	(844)	
443	Omphalic acid	C ₁₅ H ₂₂ O ₂			<i>Omphalanthus fliformis</i>	(844)	
444	(-)-Chiloscyphone	C ₁₅ H ₂₂ O		-15.7	<i>Chiloscyphus rivularis</i>	(956)	
445	(+)-Chiloscypholone	C ₁₅ H ₂₄ O ₂			<i>Chiloscyphus polyanthos</i>	(890)	
					<i>Jungermannia vulcanicola</i>	(585)	
446	Dihydrochiloscypholone	C ₁₅ H ₂₆ O ₂	80-82	+147.0	<i>Chiloscyphus polyanthos</i>	(890)	
					<i>Jungermannia vulcanicola</i>	(585)	
					<i>Lepidozia fauriana</i>	(490)	
	(+)-Dihydrochiloscypholone	C ₁₅ H ₂₆ O ₂			<i>Lepidozia fauriana</i>	(645)	

447	13-Hydroxychiloscyphone	$C_{15}H_{22}O_2$			<i>Chiloscyphus rivularis</i>	(956)
448	Chiloscypha-2,7-dione	$C_{15}H_{20}O_2$	98	-31.3	<i>Chiloscyphus rivularis</i>	(956)
449	13-Hydroxychiloscypha-2,7-dione	$C_{15}H_{20}O_3$		-40.5	<i>Chiloscyphus rivularis</i>	(956)
450	Chiloscypha-2,7,9-trione	$C_{15}H_{18}O_3$	179-181	-110	<i>Chiloscyphus rivularis</i>	(956)
451	Rivulalactone	$C_{12}H_{18}O_3$	97-99	+20.4	<i>Chiloscyphus rivularis</i>	(956)
452	4-Hydroxyoppositan-7-one	$C_{15}H_{26}O_2$	46-48	+84	<i>Chiloscyphus rivularis</i>	(956)
453	11,12-Dihydrochiloscyphone	$C_{15}H_{24}O$			<i>Lepidozia fauriana</i>	(490)
	(+)-11,12-Dihydrochiloscyphone	$C_{15}H_{24}O$			<i>Lepidozia fauriana</i>	(645)
454	(+)-7,10-Anhydro-11,12-dihydro-chiloscypholone	$C_{15}H_{24}O$			<i>Lepidozia fauriana</i>	(645)
455	α -Copaene	$C_{15}H_{24}$			<i>Drepanolejeunea</i>	(247)
					<i>madagascariensis</i>	
					<i>Dumortiera hirsuta</i>	(707)
					<i>Frullania anomala</i>	(78)
					<i>Frullania congesta</i>	(78)
					<i>Frullania fragilifolia</i>	(644)
					<i>Frullania inflata</i>	(893)
					<i>Frullania lobulata</i>	(78)
					<i>Frullania probosciphora</i>	(78)
					<i>Frullania scandens</i>	(78)
					<i>Frullania tamarisci</i>	(644)
					Unidentified <i>Frullania</i> sp.	(424)
					<i>Lepidozia fauriana</i>	(645)
					<i>Makinoa crispata</i>	(492)
					<i>Marsupella aquatica</i>	(19)
					<i>Monoclea forsteri</i>	(72)
					<i>Plagiochila bifaria</i>	(221)
						(277)
					<i>Plagiochila retrorsa</i>	(221)
					<i>Plagiochila stricta</i>	(221)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
					<i>Porella navicularis</i>	(143)	
					<i>Preissia quadrata</i>	(74)	
					<i>Radula aquilegia</i>	(223)	
					<i>Trichocolea mollissima</i>	(72)	
	(+)- α -Copaene	$\text{C}_{15}\text{H}_{24}$			<i>Preissia quadrata</i>	(433)	
456	β -Copaene	$\text{C}_{15}\text{H}_{24}$			<i>Dumortiera hirsuta</i>	(707)	
					Unidentified <i>Jungmannia</i> sp.	(494)	
					<i>Marsupella aquatica</i>	(19)	
457	α -Ylangene	$\text{C}_{15}\text{H}_{24}$			<i>Lepidozia fauriana</i>	(645)	
					<i>Lepidozia vitrea</i>	(645)	
					<i>Marsupella emarginata</i>	(17)	
					<i>Scapania undulata</i>	(16)	
458	β -Ylangene	$\text{C}_{15}\text{H}_{24}$			Unidentified <i>Jungmannia</i> sp.	(494)	
					<i>Marsupella emarginata</i>	(17)	
					<i>Scapania undulata</i>	(16)	
					<i>Trocholejeunea sandvicensis</i>	(539)	
459	(+)-Lemmalol	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Marsupella emarginata</i>	(17)	
460	α -Cubebene	$\text{C}_{15}\text{H}_{24}$			<i>Bazzania spiralis</i>	(490)	
					<i>Dumortiera hirsuta</i>	(707)	
					<i>Frullania inflata</i>	(893)	
					<i>Makinoa crispata</i>	(492)	
461	β -Cubebene	$\text{C}_{15}\text{H}_{24}$			<i>Frullania inflata</i>	(893)	
					<i>Pellia endiviifolia</i>	(492)	
					<i>Symphogyna brasiliensis</i>	(492)	
462	Cubebol (= Cubebanol)	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Conocephalum conicum</i>	(492)	
						(831)	
					<i>Conocephalum salebrosum</i>	(494)	

463	(+)-Cubebol	$C_{15}H_{26}O$		<i>Dumortiera hirsuta</i>	(492)
464	<i>ent</i> -Cubeban-11-ol	$C_{15}H_{26}O$	-60.1	<i>Preissia quadrata</i>	(433)
	Cuparene	$C_{15}H_{22}$		<i>Jackiella javanica</i>	(608)
				<i>Apometzgeria pubescens</i>	(882)
				<i>Bazzania decrescens</i>	(291)
				<i>Bazzania involuta</i>	(72)
				<i>Bazzania tridens</i>	(951)
				<i>Bazzania trilobata</i>	(930)
				<i>Chiloscyphus coalitus</i>	(72)
				<i>Chiloscyphus triacanthus</i>	(72)
				<i>Frullania falciloba</i>	(78)
				<i>Frullania probosciphora</i>	(78)
				<i>Frullania squarrosula</i>	(78)
				<i>Gymnomitrium obtusum</i>	(929)
				<i>Heteroscyphus aselliformis</i>	(490)
				<i>Lepidozia borneensis</i>	(490)
				<i>Lepidozia vitrea</i>	(645)
				<i>Marchantia polymorpha</i>	(79)
				<i>Marsupella emarginata</i>	(17)
				<i>Metacalypogeia cordifolia</i>	(748)
				<i>Metacalypogeia cordifolia</i>	(882)
					(894)
				<i>Metzgeria furcata</i>	(72)
				<i>Lepidozia concinna</i>	(72)
				<i>Lunularia cruciata</i>	(72)
				<i>Plagiochila diversifolia</i>	(330)
				<i>Preissia quadrata</i>	(74)
				<i>Radula boryana</i>	(224)
				<i>Radula carringtonii</i>	(223)
				<i>Radula nudicaulis</i>	(223)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
					<i>Radula perrottetii</i>	(492)	
					<i>Reboulia hemisphaerica</i>	(826)	
					<i>Riccardia eriocaula</i>	(929)	
					<i>Schistochila ciliata</i>	(72)	
					<i>Symphogyna podophylla</i>	(72)	
					<i>Trichocolea pluma</i>	(494)	
	(-)-Cuparene	C ₁₅ H ₂₂			<i>Lepidozia reptans</i>	(681)	
					<i>Mannia fragrans</i>	(542)	
					<i>Marchantia berteriana</i>	(72)	
					<i>Lejeunea japonica</i>	(878)	
465	(S)-(-)-Cuparene	C ₁₅ H ₂₂		+58.0	<i>Jungermannia hattoriana</i>	(590)	
	(+)-Cuparene	C ₁₅ H ₂₂			<i>Jungermannia infusca</i>	(599)	
					<i>Bazzania trilobata</i>	(930)	
466	α-Cuprenene	C ₁₅ H ₂₄			<i>Lepidozia vitrea</i>	(645)	
					<i>Marsupella emarginata</i>	(17)	
					<i>Marchantia polymorpha</i>	(492)	
					<i>Marchantia tosona</i>	(492)	
					<i>Plagiochila asplenoides</i>	(14)	
	(-)-α-Cuprenene	C ₁₅ H ₂₄			<i>Lepidozia reptans</i>	(681)	
					<i>Mannia fragrans</i>	(542)	
					<i>Reboulia hemisphaerica</i>	(929)	
467	γ-Cuprenene	C ₁₅ H ₂₄			<i>Asterella</i> sp. (?)	(71)	
					<i>Bazzania tridens</i>	(951)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Marchantia polymorpha</i>	(492)	
					<i>Marchantia tosona</i>	(492)	

468	δ -Cuprenene	$C_{15}H_{24}$	<i>Mylia taylorii</i>	(922)	
			<i>Radula perrottetii</i>	(826)	
			<i>Symphogyna brasiliensis</i>	(492)	
			<i>Asterella echinella</i>	(492)	
			<i>Bazzania madagassa</i>	(291)	
				(293)	
			<i>Bazzania trilobata</i>	(485)	
			<i>Lepidozia fairiana</i>	(645)	
			<i>Marchantia polymorpha</i>	(492)	
			<i>Marsipella aquatica</i>	(19)	
			<i>Mylia taylorii</i>	(922)	
			<i>Reboulia hemisphaerica</i>	(492)	
			<i>Symphogyna brasiliensis</i>	(492)	
469 470 471 472	$(-)-\delta$ -Cuprenene	$C_{15}H_{24}$	<i>Bazzania trilobata</i>	(930)	
			<i>Calypogeia muelleriana</i>	(933)	
			<i>Mammia fragrans</i>	(542)	
			<i>Reboulia hemisphaerica</i>	(929)	
			<i>Bazzania tridens</i>	(959)	
			<i>Jungermannia hattoriana</i>	(590)	
			<i>Jungermannia infusca</i>	(595)	
			<i>Jungermannia hattoriana</i>	(590)	
			<i>Jungermannia infusca</i>	(595)	
				(600)	
			<i>Jungermannia hattoriana</i>	(590)	
			<i>Jungermannia infusca</i>	(591)	
				(595)	
473	$(+)-3$ - <i>epi</i> -Cuprenenol (= Neocuprenenol)	$C_{15}H_{26}O$		(600)	X-ray (continued)
			<i>Jungermannia hattoriana</i>	(590)	
			<i>Jungermannia infusca</i>	(600)	
				(590)	
				(591)	
				(595)	
				(600)	
				(590)	
				(591)	
				(595)	
				(600)	
				(590)	
				(591)	
				(595)	

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
474	Rosulantol	$\text{C}_{15}\text{H}_{24}\text{O}_2$			<i>Jungermannia hattoriana</i> <i>Jungermannia infusca</i>	(590) (591) (595)	
475	<i>epi</i> -Rosulantol	$\text{C}_{15}\text{H}_{24}\text{O}_2$	139-140	+155.4	<i>Jungermannia infusca</i>	(600) (595)	X-ray
476	(-)- α -Microbiotene	$\text{C}_{15}\text{H}_{24}$			<i>Mannia fragrans</i>	(542)	
477	(+)- β -Microbiotene	$\text{C}_{15}\text{H}_{24}$			<i>Mannia fragrans</i>	(542)	
478	Grimaldone	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Mannia fragrans</i>	(542)	
479	(-)-Cyclocupar-2-en-10-one	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Mannia fragrans</i>	(542)	
480	Microbiotol	$\text{C}_{15}\text{H}_{26}\text{O}_2$			<i>Jungermannia infusca</i>	(599)	
481	α -Cuparenol	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Lepidozia concinna</i>	(72)	
482	1-Cuparenol	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Lejeunea aquatica</i>	(878)	
483	2-Cuparenol (= Cuparophenol, δ -Cuparenol)	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Apometzgeria pubescens</i> <i>Bazzania involuta</i> <i>Bazzania tricrenata</i> <i>Bazzania tridens</i> <i>Bazzania yoshinagana</i> <i>Dunortiera hirsuta</i> <i>Lejeunea aquatica</i> <i>Lejeunea flava</i> <i>Lejeunea japonica</i> <i>Lunularia cruciata</i> <i>Marchantia berteriana</i> <i>Marchantia polymorpha</i> <i>Mastigophora dicladus</i>	(882) (72) (84) (951) (821) (876) (878) (878) (878) (72) (72) (79) (425) (494)	

484	(-)-2-Cuparenol α -Cuparenone	$C_{15}H_{22}O$ $C_{15}H_{20}O$		<i>Metacalypogeia cordifolia</i> (882) <i>Metzgeria furcata</i> (72) <i>Riccardia eriocaula</i> (72) <i>Bazzania trilobata</i> (930) <i>Lepidozia concinna</i> (72) <i>Symphogyna podophylla</i> (72) <i>Symphogyna prolifera</i> (72) <i>Riccardia eriocaula</i> (72) <i>Lepidozia concinna</i> (72) <i>Apometzgeria pubescens</i> (882) <i>Lejeunea aquatica</i> (878) <i>Lejeunea flava</i> (878) <i>Lejeunea japonica</i> (878) <i>Lejeunea aquatica</i> (878) <i>Lejeunea flava</i> (878) <i>Lejeunea japonica</i> (878) <i>Apometzgeria pubescens</i> (882) <i>Lejeunea aquatica</i> (878) <i>Lejeunea flava</i> (878) <i>Lejeunea aquatica</i> (878) <i>Lejeunea aquatica</i> (878) <i>Lejeunea aquatica</i> (878) <i>Lejeunea aquatica</i> (878) <i>Lejeunea aquatica</i> (878) <i>Lejeunea aquatica</i> (878) <i>Lejeunea aquatica</i> (878) <i>Bazzania decrescens</i> (291) <i>Bazzania decrescens</i> (291) <i>Jungermannia infusca</i> (591) (595) (600) (591) (595)
485	1,2-Dihydroxy- α -cuparenone	$C_{15}H_{20}O_3$		
486	Dihydro- α -cuparenone	$C_{15}H_{22}O$		
487	(-)-1,2-Cuparenediol	$C_{15}H_{22}O_2$		
488	1,4-Cuparenediol	$C_{15}H_{22}O_2$	+171.6	
489	Cuparene-1,4-quinone	$C_{15}H_{20}O_2$		
490	Deoxyhellicobasidin	$C_{15}H_{26}O_3$		
491	Aquaticenol [(7S,7'S)-(-)-4,4'-bis-1,2-Cuparenediol]	$C_{30}H_{42}O_4$	145-146	-23.4
492	2-Hydroxy-4-methoxycuparene	$C_{16}H_{24}O_2$		-52.2
493	2-Hydroxy-5-methoxycuparene	$C_{16}H_{24}O_2$		
494	(2S,5R)-Peroxycupar-3-ene	$C_{15}H_{22}O_2$	77-78	+28.9
495	(2R,5S)-Peroxycupar-3-ene	$C_{15}H_{22}O_2$	+136.2	

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
496	<i>ent</i> -3,6-Peroxocupar-1-ene	C ₁₅ H ₂₄ O ₂		+61.2	<i>Jungmannia infusca</i>	(595) (600)	
496a	<i>ent</i> -3,6-Peroxocupar-1-ene diastereomer	C ₁₅ H ₂₄ O ₂		+75.0	<i>Jungmannia infusca</i>	(595) (600)	
497	6β,10β-Epoxycupar-3-ene	C ₁₅ H ₂₄ O		+69.3	<i>Reboulia hemisphaerica</i>	(889)	
498	Secocuparenal	C ₁₅ H ₂₄ O ₂		-59.1	<i>Jungmannia infusca</i>	(599)	
499	Infuscol A	C ₁₅ H ₂₄	73-75	-6.7	<i>Jungmannia infusca</i>	(600)	X-ray
500	Infuscol B	C ₁₅ H ₂₄		+35.7	<i>Jungmannia infusca</i>	(600)	
501	Infuscol C	C ₁₅ H ₂₆ O ₃	140-142	+3.7	<i>Jungmannia infusca</i>	(600)	X-ray
502	Infuscol D	C ₁₅ H ₂₆ O ₃		+34.4	<i>Jungmannia infusca</i>	(600)	
503	Infuscol E	C ₁₅ H ₂₆ O ₂		+10.5	<i>Jungmannia infusca</i>	(600)	
504	(+)-δ-Cuprenen-4α-ol	C ₁₅ H ₂₄ O		+88.7	<i>Jungmannia infusca</i>	(600)	
505	(+)-Cyclopropanecuparenol	C ₁₅ H ₂₆ O		+15.0	<i>Jungmannia infusca</i>	(600)	
506	(-)-Cyclopropanecuparenol (= (2S,6S)-Cyclo-(7S)-cuparan-(3S)-ol)	C ₁₅ H ₂₆ O			<i>Cryptothallus mirabilis</i>	(692)	
					<i>Marchantia polymorpha</i>	(492)	
					<i>Reboulia hemisphaerica</i>	(436)	
507	6β,10β-epoxycupar-2-ene	C ₁₅ H ₂₄ O		+69.3	<i>Reboulia hemisphaerica</i>	(436)	
508	Herbertene	C ₁₅ H ₂₂			<i>Asterella australis</i>	(72)	
					<i>Bazzania involuta</i>	(72)	
					<i>Chandonanthus hirtellus</i>	(423) (494)	
					<i>Dendromastigophora flagelifera</i>	(72)	
					<i>Herbertus aduncus</i>	(635) (137)	
					<i>Herbertus borealis</i>	(323)	
					<i>Herbertus sakuraii</i>	(137) (323) (365)	

509	α -Herbertenol	$C_{15}H_{22}O$	<i>Mastigophora dielados</i>	(287)
				(321)
				(425)
				(490)
				(494)
				(748)
			<i>Metacalypogeia alternifolia</i>	(70)
			<i>Wetsteinia schusterana</i>	(72)
			<i>Asterella australis</i>	(423)
			<i>Chandonanthus hirtellus</i>	(494)
		<i>Dendromastigophora</i>	(72)	
		<i>flagellifera</i>	(635)	
		<i>Dendromastigophora</i> sp.	(615)	
		<i>Herbertus aduncus</i>	(137)	
			(323)	
		<i>Herbertus borealis</i>	(137)	
		<i>Herbertus sakuraii</i>	(321)	
			(323)	
			(365)	
		<i>Marchantia paleacea</i>	(424)	
	<i>Mastigophora dielados</i>	(426)		
		(425)		
		(490)		
		(494)		
	<i>Plagiochila retrospectans</i>	(72)		
	<i>Wetsteinia schusterana</i>	(70)		
	<i>Dendromastigophora</i>	(616)		
	<i>flagellifera</i>			
	<i>Mastigophora dielados</i>	(287)		
		(425)		

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
510	γ -Herbertenol	$\text{C}_{15}\text{H}_{22}\text{O}$		-62.9	<i>Tylimanthus renifolius</i>	(213)	
					<i>Dendromastigophora flagellifera</i>	(635)	
	(-)- γ -Herbertenol	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Tylimanthus renifolius</i>	(213)	
511	β -Herbertenol	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Dendromastigophora flagellifera</i>	(72)	
					<i>Herbertus aduncus</i>	(635)	
					<i>Mastigophora diclados</i>	(137)	
512	(-)- β -Herbertenol	$\text{C}_{15}\text{H}_{22}\text{O}$				(425)	
	Herbertene-1,2-diol	$\text{C}_{15}\text{H}_{22}\text{O}_2$				(490)	
					<i>Mastigophora diclados</i>	(494)	
					<i>Herbertus aduncus</i>	(287)	
					<i>Herbertus sakuraii</i>	(137)	
						(323)	
						(323)	
						(365)	
					<i>Mastigophora diclados</i>	(287)	
				-33.5		(425)	
						(490)	
						(494)	
513	Herbertene-2,3-diol	$\text{C}_{15}\text{H}_{22}\text{O}_2$			<i>Mastigophora diclados</i>	(490)	
514	Herbertene-1,12-diol	$\text{C}_{15}\text{H}_{22}\text{O}_2$			<i>Dendromastigophora flagellifera</i>	(635)	
515	(-)-Herbertene-1,12-diol	$\text{C}_{15}\text{H}_{22}\text{O}_2$			<i>Tylimanthus renifolius</i>	(213)	
	(-)- α -Formylherbertenol	$\text{C}_{15}\text{H}_{20}\text{O}_2$			<i>Mastigophora diclados</i>	(287)	
	Mastigophoric acid methyl ester	$\text{C}_{16}\text{H}_{22}\text{O}_3$			<i>Mastigophora diclados</i>	(287)	
516	1,2-Dihydroxyherberten-12-al	$\text{C}_{15}\text{H}_{20}\text{O}_3$			<i>Herbertus aduncus</i>	(323)	
	(-)-1,2-Dihydroxyherberten-12-al	$\text{C}_{15}\text{H}_{20}\text{O}_3$	153-155	-11	<i>Herbertus aduncus</i>	(137)	

518	Methyl 1,2-dihydroxyherberten-12-oate	$C_{16}H_{22}O_4$		<i>Herbertus aduncus</i>	(137)
519	1,13-Dihydroxyherbertene	$C_{13}H_{22}O_2$	-26.0	<i>Herbertus sakuraii</i>	(323)
520	1,14-Dihydroxyherbertene	$C_{13}H_{22}O_2$		<i>Herbertus aduncus</i>	(365)
			+33.5	<i>Herbertus sakuraii</i>	(323)
521	1,15-Dihydroxyherbertene	$C_{13}H_{22}O_2$	-66.9	<i>Herbertus sakuraii</i>	(365)
522	12-Methoxyherbertene-1,2-diol	$C_{16}H_{24}O_3$	-43.2	<i>Herbertus aduncus</i>	(323)
523	Herberteneacetal	$C_{13}H_{20}O_2$		<i>Herbertus sakuraii</i>	(365)
524	Herbertenolide	$C_{13}H_{18}O_2$	+19.0	<i>Herbertus aduncus</i>	(323)
				<i>Herbertus sakuraii</i>	(365)
525	Herbertenone A	$C_{13}H_{22}O_2$		<i>Dendromastigophora flagellifera</i>	(635)
526	Herbertenone B	$C_{13}H_{22}O_2$	-11.9	<i>Herbertus sakuraii</i>	(323)
				<i>Dendromastigophora flagellifera</i>	(365)
				<i>Herbertus sakuraii</i>	(635)
527	1,4-Peroxyherbert-5-ene	$C_{13}H_{24}O_2$	-3.9	<i>Lepidozia setigera</i>	(323)
528	Mastigophorene A	$C_{30}H_{42}O_4$	-11.9	<i>Herbertus sakuraii</i>	(365)
				<i>Mastigophora dicladia</i>	(425)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
529	Mastigophorene B	$\text{C}_{30}\text{H}_{42}\text{O}_4$			<i>Herbertus sakuraii</i>	(323) (365)	
530	Mastigophorene C	$\text{C}_{30}\text{H}_{42}\text{O}_4$			<i>Herbertus sakuraii</i>	(323) (365)	
531	Mastigophorene D	$\text{C}_{30}\text{H}_{42}\text{O}_4$		-60.7	<i>Mastigophora dicladus</i>	(287) (425)	
532	(+)- <i>trans</i> -Dauca-4(11),8-diene	$\text{C}_{15}\text{H}_{24}$		-68.2	<i>Mastigophora dicladus</i>	(287) (425)	
533	<i>trans</i> -Dauca-4(11),7-diene	$\text{C}_{15}\text{H}_{24}$			<i>Bazzania trilobata</i>	(930)	
534	Isodauca-4,7(14)-diene	$\text{C}_{15}\text{H}_{24}$			<i>Symphogyna brasiliensis</i>	(492)	
535	(+)-6,11-Epoxyisodaucane	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Radula perrottetii</i>	(492)	
536	Hercynolactone	$\text{C}_{15}\text{H}_{26}\text{O}_2$			<i>Tritomaria polita</i>	(18)	
537	Drimenene	$\text{C}_{15}\text{H}_{24}$			<i>Barbilophozia barbata</i>	(583)	
538	Drimenol	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Barbilophozia hatcheri</i>	(593) (596)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Bazzania decrescens</i>	(291)	
					<i>Bazzania involuta</i>	(72)	
					<i>Bazzania tricrenata</i>	(84)	
					<i>Bazzania trilobata</i>	(582) (715)	
					<i>Bazzania praerupta</i>	(930)	
					<i>Corsinia coriandrina</i>	(490) (79)	
					<i>Symphogyna podophylla</i>	(72)	
					<i>Porella vernicosa</i>	(637)	Cell culture
	(+)-Drimenol	$\text{C}_{15}\text{H}_{26}\text{O}$		+54.4	<i>Mastigophora dicladus</i>	(425)	

539	Albicanol	$C_{15}H_{26}O$	<i>Bazzania praerupta</i> <i>Bazzania tridens</i> <i>Bazzania yoshinagana</i> <i>Cephalozitiella recurvifolia</i> <i>Frullania monocera</i> <i>Porella navicularis</i> <i>Bazzania trilobata</i> <i>Bazzania decrescens</i> <i>Bazzania yoshinagana</i> <i>Porella canariensis</i> <i>Porella fauriei</i> <i>Porella canariensis</i> <i>Porella canariensis</i> <i>Makinoa crispata</i> <i>Porella canariensis</i> <i>Porella fauriei</i> <i>Porella vernicosa</i> <i>Porella canariensis</i> <i>Porella fauriei</i> <i>Porella canariensis</i> <i>Porella fauriei</i> <i>Porella vernicosa</i> <i>Lepicolea ochroleuca</i> <i>Plagiochila aerea</i>	(490) (951) (821) (955) (78) (143) (715) (291) (821) (179) (821) (582) (604) (179) (604) (492) (179) (582) (604) (821) (637) (582) (604) (821) (179) (821) (637) (478) (334)
540	Drimenal	$C_{15}H_{24}O$		
541	Drimenyl caffeate	$C_{24}H_{32}O_4$		
542	Albicanyl caffeate	$C_{24}H_{32}O_4$		
543	Drimeninol	$C_{15}H_{24}O_2$		
544	Isodrimeninol	$C_{15}H_{24}O_2$		
545	Drimenin	$C_{15}H_{22}O_2$		
546	Cinnamolide	$C_{15}H_{22}O_2$		
547	<i>cis</i> -Dihydrocinnamolide	$C_{15}H_{24}O_2$		
548	Polygodial	$C_{15}H_{22}O_2$		
549	Isopolygodial	$C_{15}H_{22}O_2$		
550	Peculiaroxide	$C_{15}H_{26}O$		

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
					<i>Plagiochila bifaria</i>	(221)	
					<i>Plagiochila dusenii</i>	(277)	
					<i>Plagiochila maderensis</i>	(333)	
					<i>Plagiochila retrorsa</i>	(32)	
						(221)	
						(221)	
					<i>Plagiochila rutilans</i>	(698)	
					<i>Plagiochila stricta</i>	(693)	
						(221)	
						(699)	
					<i>Plagiochila validissima</i>	(32)	
551	Blepharostol	C ₁₅ H ₂₆ O		+27.8	<i>Blepharostoma trichophyllum</i>	(215)	in vitro Culture
552	Blepharostol caffeate	C ₂₄ H ₃₂ O ₄		-2.5	<i>Bazzania novae-zelandiae</i>	(899)	
553	Dumortenol	C ₁₅ H ₂₄ O			<i>Dumortiera hirsuta</i>	(901)	X-ray
554	Dumortenol-6,7-epoxide	C ₁₅ H ₂₄ O ₂			<i>Dumortiera hirsuta</i>	(96)	
555	Dumortane-type 1	C ₁₅ H ₂₂ O			<i>Dumortiera hirsuta</i>	(876)	
						(96)	
						(424)	
556	Dumortane-type 2	C ₁₅ H ₂₂ O ₂			<i>Dumortiera hirsuta</i>	(426)	
557	Rearranged dumortane-type	C ₁₅ H ₂₄ O ₂			<i>Dumortiera hirsuta</i>	(96)	
558	Nordumortane-type	C ₁₄ H ₂₂ O ₂			<i>Dumortiera hirsuta</i>	(96)	
559	Eremophilene	C ₁₅ H ₂₄			<i>Frullania serrata</i>	(490)	
					<i>Frullania tamarisci</i>	(644)	

				<i>Frullania tamarisci</i> subsp. <i>obscura</i>	(492)
				<i>Radula aquilegia</i>	(223)
				<i>Radula lindenbergiana</i>	(223)
				<i>Radula nudicaulis</i>	(223)
				<i>Radula perrottetii</i>	(492)
					(826)
				<i>Radula wichurae</i>	(223)
				<i>Tritomaria polita</i>	(18)
				<i>Trocholejeunea sandvicensis</i>	(539)
				<i>Radula perrottetii</i>	(826)
				Unidentified <i>Frullania</i> sp.	(424)
				<i>Frullania anomala</i>	(78)
				<i>Marsupella emarginata</i>	(17)
				<i>Trocholejeunea sandvicensis</i>	(539)
				<i>Marchantia polymorpha</i> subsp. <i>aquatica</i>	(680)
				<i>Frullania muscicola</i>	(443)
				<i>Frullania dilatata</i>	(578)
				<i>Frullania dilatata</i>	(578)
				<i>Frullania brasiliensis</i>	(98)
				<i>Frullania brasiliensis</i>	(98)
				<i>Frullania lobulata</i>	(78)
				<i>Frullania media</i>	(78)
				<i>Frullania probosciphora</i>	(78)
				<i>Frullania lobulata</i>	(78)
				<i>Frullania media</i>	(78)
				<i>Frullania probosciphora</i>	(78)
					(continued)
560	Eremophila-1(10),6-diene	C ₁₅ H ₂₄			
560a	Eremophila-1(10),7-diene	C ₁₅ H ₂₄			
561	Eremophila-1(10),8,11-triene	C ₁₅ H ₂₂			
562	(-)-7- <i>epi</i> -Eremophila-1(10),8,11-triene	C ₁₅ H ₂₂			
563	(-)-1(10),11-Eremophiladien-9 β -ol	C ₁₅ H ₂₄ O	-81		
564	4 β ,5 α ,6 α ,7 α -1(10),11(13)-Eremophiladiene-12,6-olide	C ₁₅ H ₂₀ O ₂	-0.8		
565	Dilatanolide A	C ₁₅ H ₂₂ O ₂	58-60		
566	Dilatanolide B	C ₁₅ H ₂₀ O ₂	57-59		
567	5- <i>epi</i> -Dilatanolide A	C ₁₅ H ₂₂ O ₂	106-107		X-ray
568	5- <i>epi</i> -Dilatanolide B	C ₁₅ H ₂₀ O ₂	-21.5		X-ray
569	Eremofrullanolide	C ₁₅ H ₂₀ O ₂	+50.8		
570	Dihydroeremofrullanolide	C ₁₅ H ₂₂ O ₂			

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
571	4,5-di- <i>epi</i> -Aristolochene	C ₁₅ H ₂₄			<i>Frullania tamarisci</i> subsp. <i>obscura</i>	(492)	
					<i>Radula perrottetii</i>	(826)	
					<i>Tritomaria polita</i>	(18)	
572	1(10)-Valencen-7 β -ol (-)-1(10)-Valencen-7 β -ol	C ₁₅ H ₂₆ O C ₁₅ H ₂₆ O			<i>Trocholejeunea sandvicensis</i> <i>Lophozia ventricosa</i>	(539) (486)	
					<i>Calypogeia muelleriana</i>	(933)	
573	(+)-Aristolochene	C ₁₅ H ₂₄			<i>Lepidozia reptans</i>	(681)	
	(-)-Aristolochene	C ₁₅ H ₂₄			<i>Porella arboris-vitae</i>	(707)	
574	Valencene	C ₁₅ H ₂₄			<i>Dumortiera hirsuta</i>	(707)	
					<i>Bryopteris flicina</i>	(604)	
					<i>Frullania pycnantha</i>	(78)	
					Unidentified <i>Frullania</i> sp.	(424)	
					<i>Porella perrottetiana</i>	(424)	
					<i>Radula aquilegia</i>	(223)	
					<i>Radula carringtonii</i>	(223)	
					<i>Radula complanata</i>	(223)	
					<i>Radula wichurae</i>	(223)	
					<i>Trichocolea pluma</i>	(494)	
					<i>Trocholejeunea sandvicensis</i>	(492)	
	(+)-Valencene	C ₁₅ H ₂₄			<i>Dumortiera hirsuta</i>	(707)	
					<i>Marsipella emarginata</i>	(17)	
					<i>Porella acutifolia</i> subsp. <i>tosana</i>	(322)	
574a	Nootkatene	C ₁₅ H ₂₄			Unidentified <i>Frullania</i> sp.	(424)	
					<i>Dumortiera hirsuta</i>	(424)	
575	α -Selinene	C ₁₅ H ₂₄			<i>Bazzania praerupta</i>	(490)	
					<i>Bazzania spiralis</i>	(490)	

576	(+)- α -Selinene (= Eudesma-3,11-diene)	C ₁₅ H ₂₄	<i>Diplophyllum albicans</i> (15)
			<i>Frullania aterrima</i> var. <i>aterrima</i> (78)
			<i>Frullania inflata</i> (893)
			<i>Lophocolea bidentata</i> (679)
			<i>Lunularia cruciata</i> (72)
			<i>Marchantia foliacea</i> (72)
			<i>Marchantia paleacea</i> (424)
			(426)
			<i>Marchantia polymorpha</i> (72)
			<i>Plagiochila suborbiculata</i> (79)
577			<i>Radula carringtonii</i> (223)
			<i>Radula complanata</i> (223)
			<i>Trichocolea pluma</i> (494)
			<i>Tritomaria quinqueidentata</i> (928)
			<i>Marsupella alpina</i> (17)
			<i>Tritomaria polita</i> (18)
			<i>Tylimanthus tenellus</i> (896)
			<i>Radula aquilegia</i> (223)
			<i>Radula carringtonii</i> (223)
			<i>Dumortiera hirsuta</i> (707)
577	(-)-7- <i>epi</i> - α -Selinene	C ₁₅ H ₂₄	<i>Frullania inflata</i> (893)
	β -Selinene	C ₁₅ H ₂₄	Unidentified <i>Frullania</i> sp. (424)
			<i>Marchantia paleacea</i> (426)
			<i>Marchantia paleacea</i> var. <i>diptera</i> (424)
			(492)
			<i>Plagiochila retrorsa</i> (221)
			<i>Plagiochila suborbiculata</i> (72)
			<i>Porella navicularis</i> (143)
			<i>Radula aquilegia</i> (223)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
578	(-)- β -Selinene (= Eudesma-4 (15), 11-diene)	$\text{C}_{15}\text{H}_{24}$		-30.9	<i>Radula carringtonii</i>	(223)	
					<i>Tylimanthus tenellus</i>	(896)	
	δ -Selinene	$\text{C}_{15}\text{H}_{24}$			<i>Diplophyllum albicans</i>	(15)	
					<i>Frullania pycnantha</i>	(78)	
					<i>Lepidozia vitrea</i>	(645)	
					<i>Plagiochila dusenii</i>	(32)	
579	(+) δ -Selinene	$\text{C}_{15}\text{H}_{24}$			Unidentified <i>Plagiochila</i> sp.	(494)	
					<i>Symphodyna brasiliensis</i>	(492)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Calypogeia fissa</i>	(931)	
					<i>Calypogeia muelleriana</i>	(933)	
					<i>Plagiochila asplenoides</i>	(14)	
					<i>Preissia quadrata</i>	(433)	
					<i>Frullania atterrma</i> var. <i>atterma</i>	(78)	
					<i>Frullania fragilifolia</i>	(644)	
					<i>Frullania tamarisci</i>	(644)	
					<i>Marchantia paleacea</i>	(424)	
						(426)	
580	(-)-Selina-4,11-diene	$\text{C}_{15}\text{H}_{24}$			<i>Plagiochila dusenii</i>	(32)	
					<i>Plagiochila validissima</i>	(32)	
					<i>Marsupella alpina</i>	(17)	
					<i>Conocephalum conicum</i>	(543)	
					<i>Radula perrottetii</i>	(826)	
581	Selina-3,7-diene	$\text{C}_{15}\text{H}_{24}$			<i>Pellia endiviifolia</i>	(492)	
					<i>Radula perrottetii</i>	(826)	

582	Selina-3,7(11)-diene	C ₁₅ H ₂₄	<i>Symphyogyna brasiliensis</i>	(492)
583	(-)-Selin-11-en-4 α -ol	C ₁₅ H ₂₄ O	<i>Tritomaria polita</i>	(18)
			<i>Conocephalum conicum</i>	(543)
				(880)
584	(+)- <i>ent</i> -Selin-11-en-4 β -ol	C ₁₅ H ₂₄ O	<i>Riccardia nagasakiensis</i>	(141)
585	Selina-4(15),5-diene	C ₁₅ H ₂₄	<i>Trocholejeunea sandvicensis</i>	(539)
586	(+)-Selina-4,11-dien-9 α -ol	C ₁₅ H ₂₄ O	<i>Marsupella aquatica</i>	(17)
587	(-)- <i>trans</i> -Selina-4(15),11-dien-5-ol	C ₁₅ H ₂₄ O	<i>Marsupella alpina</i>	(17)
588	(+)- <i>cis</i> -Selina-4(15),11-dien-5-ol	C ₁₅ H ₂₄ O	<i>Marsupella alpina</i>	(17)
589	Selina-4(15),11-dien-8-ol	C ₁₅ H ₂₄ O	<i>Lophozia ventricosa</i>	(486)
590	(+)-8,9-Epoxy Selina-4,11-diene	C ₁₅ H ₂₂ O	<i>Marsupella alpina</i>	(17)
591	α -Helmiscapene	C ₁₅ H ₂₄	<i>Radula aquilegia</i>	(223)
			<i>Radula jonesii</i>	(223)
			<i>Radula nudicaulis</i>	(223)
			<i>Radula perrottetii</i>	(826)
592	β -Helmiscapene	C ₁₅ H ₂₄	<i>Radula wichurae</i>	(223)
			<i>Radula perrottetii</i>	(826)
593	Rosifoliol	C ₁₅ H ₂₆ O	<i>Radula nudicaulis</i>	(223)
			<i>Bazzania japonica</i>	(485)
			<i>Frullania tamarisci</i>	(644)
			<i>Kurzia trichoclados</i>	(922)
			<i>Lepidozia vitrea</i>	(645)
			<i>Lophozia ventricosa</i>	(486)
			<i>Mylia nuda</i>	(922)
			<i>Mylia taylorii</i>	(922)
			<i>Plagiochila asplenoides</i>	(14)
				(604)
	(-)- <i>ent</i> -Rosifoliol	C ₁₅ H ₂₆ O	<i>Bazzania trilobata</i>	(930)
			<i>Calypogeia fissa</i>	(931)
			<i>Calypogeia muelleriana</i>	(933)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
594	(-)-7- <i>epi</i> -Isojunenol	C ₁₅ H ₂₆ O			<i>Tritomaria quinqueidentata</i>	(928)	
595	(+)-7- <i>epi</i> -Junenol	C ₁₅ H ₂₆ O			<i>Tritomaria quinqueidentata</i>	(928)	
596	(-)-Cascarilladiene (= Eudesma-3,7-diene)	C ₁₅ H ₂₄			<i>Preissia quadrata</i>	(433)	
597	Eudesma-5,7(11)-diene	C ₁₅ H ₂₄			Unidentified <i>Plagiochila</i> sp.	(494)	
					<i>Symphogyna brasiliensis</i>	(492)	
598	Eudesma-3,5,11-triene	C ₁₅ H ₂₂			<i>Marsupella alpina</i>	(17)	
599	Eudesma-1,4(15),11-triene	C ₁₅ H ₂₂			<i>Plagiochila bifaria</i>	(277)	
600	α -Eudesmol	C ₁₅ H ₂₆ O			<i>Marchantia polymorpha</i>	(79)	
					<i>Trichocolea pluma</i>	(494)	
601	(-)- α -Eudesmol	C ₁₅ H ₂₆ O		-6.9	<i>Porella perrottetiana</i>	(892)	
	β -Eudesmol	C ₁₅ H ₂₆ O			<i>Lunularia cruciata</i>	(72)	
					<i>Marchantia pileata</i>	(72)	
602	γ -Eudesmol	C ₁₅ H ₂₆ O			<i>Marchesinia mackaii</i>	(220)	
603	<i>ent</i> -Eudesm-3-en-7 α -ol	C ₁₅ H ₂₆ O		+14.3	<i>Trichocolea pluma</i>	(494)	
					<i>Lepidozia fauriana</i>	(490)	
					<i>Lepidozia vitrea</i>	(645)	
604	(-)-(5 <i>R</i> ,7 <i>S</i> ,10 <i>R</i>)-Eudesm-3-en-7 α -ol	C ₁₅ H ₂₆ O		-23.2	<i>Chiloscyphus polyanthos</i>	(871)	X-ray
605	Eudesm-4(15)-en-7 α -ol	C ₁₅ H ₂₆ O		+8.7	<i>Lepidozia vitrea</i>	(890)	
						(645)	
606	Eudesm-4-en-7-ol			-8.9	<i>Chiloscyphus polyanthos</i>	(871)	
	(-)-Eudesm-4-en-7 α -ol	C ₁₅ H ₂₆ O			<i>Lophozia ventricosa</i>	(890)	
					<i>Lepidozia fauriana</i>	(486)	
					<i>Lepidozia vitrea</i>	(645)	
607	Eudesm-11-en-4 α -ol	C ₁₅ H ₂₆ O			<i>Marchantia foliacea</i>	(645)	
					<i>Saccogyna viticulosa</i>	(347)	
						(276)	

608	Isointermedeol	C ₁₅ H ₂₆ O	36-38	-11.2	<i>Chiloscyphus rivularis</i>	(956)
609	(-)-Eudesm-7(11)-en-4 α -ol	C ₁₅ H ₂₆ O			<i>Chiloscyphus polyanthos</i>	(890)
610	<i>ent</i> -Eudesma-4(15),11-dien-8 β -ol	C ₁₅ H ₂₄ O			<i>Plagiochilton conjugatus</i>	(72)
						(616)
611	(+)-Eudesma-4,11-dien-8 α -ol	C ₁₅ H ₂₄ O			<i>Diplophyllum albicans</i>	(15)
612	(+)-Eudesm-4(15)-ene-6 β ,7 α -diol	C ₁₅ H ₂₆ O ₂		+4.6	<i>Lepidozia vitrea</i>	(871)
613	(+)-Eudesm-4(15)-ene-6 α ,7 α -diol	C ₁₅ H ₂₆ O ₂			<i>Chiloscyphus polyanthos</i>	(890)
614	(+)-Eudesm-3-ene-6 β ,7 α -diol	C ₁₅ H ₂₆ O ₂			<i>Lepidozia vitrea</i>	(497)
						(871)
615	Eudesm-3-en-6 α -acetox-7 α -ol	C ₁₇ H ₂₈ O ₃		-43.8	<i>Lepidozia vitrea</i>	(497)
						(871)
616	6 α -Acetox-4 α ,7 β -dihydroxy- <i>ent</i> -eudesmane	C ₁₇ H ₃₀ O ₄	153-154	+31.6	<i>Lepidozia fauriana</i>	(747)
617	6 α -Acetox-7 β -hydroxy- <i>ent</i> -eudesm-4-ene	C ₁₇ H ₂₈ O ₃		+45.9	<i>Lepidozia fauriana</i>	(747)
618	6 α -Acetox-7 β -hydroxy- <i>ent</i> -eudesm-4(15)-ene	C ₁₇ H ₂₈ O ₃		+65.4	<i>Lepidozia fauriana</i>	(747)
619	6 β -Acetox-7 β -hydroxy- <i>ent</i> -eudesm-4(15)-ene	C ₁₇ H ₂₈ O ₃			<i>Bazzania tridens</i>	(152)
620	4 α ,7 β -Dihydroxy- <i>ent</i> -eudesmane	C ₁₅ H ₂₈ O ₂		+4.5	<i>Lepidozia fauriana</i>	(747)
621	4 β H-5 α ,7 β -Dihydroxy- <i>ent</i> -eudesmane	C ₁₅ H ₂₈ O ₂		+25.7	<i>Lepidozia fauriana</i>	(747)
622	<i>ent</i> -4(15)-Eudesmene-1 β ,6 α -diol	C ₁₅ H ₂₆ O ₂		-36.8	<i>Jackiella javanica</i>	(608)
623	<i>ent</i> -Eudesm-4-en-6-one [(7 <i>R</i> ,10 <i>S</i>)]	C ₁₅ H ₂₄ O			<i>Plagiochila bifaria</i>	(221)
						(277)
624	<i>ent</i> -7 α -Hydroxyeudesm-4-en-6-one [(7 <i>S</i> ,10 <i>S</i>)]	C ₁₅ H ₂₄ O ₂			<i>Plagiochila maderensis</i>	(221)
					<i>Plagiochila retrorsa</i>	(221)
					<i>Plagiochila stricta</i>	(221)
					<i>Plagiochila bifaria</i>	(221)
						(277)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
625	<i>ent</i> -Eudesma-4(15)-en-6-one [(−)-(5 <i>R</i> , 7 <i>R</i> , 10 <i>S</i>)]	C ₁₅ H ₂₄ O			<i>Plagiochila maderensis</i> <i>Plagiochila retrorsa</i> <i>Plagiochila stricta</i> <i>Plagiochila bifaria</i>	(221) (221) (221) (221) (277)	
626	Furanoeudesma-4(15),7,11-trien-5 <i>α</i> -ol	C ₁₅ H ₂₀ O ₂			<i>Plagiochila maderensis</i> <i>Plagiochila retrorsa</i> <i>Plagiochila stricta</i> <i>Lophocolea heterophylla</i>	(221) (221) (221) (678)	
627	Eudesma-4(15),11-dien-8-one	C ₁₅ H ₂₂ O			<i>Lophozia ventricosa</i>	(486)	
628	(+)-Eudesma-3,11-dien-8-one	C ₁₅ H ₂₂ O			<i>Tritomaria polita</i>	(18)	
629	<i>ent</i> - <i>α</i> -Cyclogermacrene (= (+)-Eudesma-3,7(11)-dien-8-one)	C ₁₅ H ₂₂ O			Unidentified <i>Chiloscyphus</i> sp. <i>Tritomaria polita</i>	(635) (18)	
630	(+)-3,4,(4 <i>aR</i>),7,8,(8 <i>aR</i>)-Hexahydro-5,8a-dimethylnaphthalen-2(1 <i>H</i>)-one	C ₁₂ H ₁₈ O			<i>Lophozia ventricosa</i> <i>Tritomaria polita</i>	(486) (18)	
631	(−)- <i>ent</i> - <i>β</i> -Cyclogermacrene (= (−)-Eudesma-4(15),7(11)-dien-8-one)	C ₁₅ H ₂₂ O		−90.5	Unidentified <i>Chiloscyphus</i> sp. <i>Lophozia ventricosa</i>	(635) (486)	
632	4,15-Epoxy- <i>ent</i> - <i>β</i> -cyclogermacrene	C ₁₅ H ₂₂ O ₂		−6.7	Unidentified <i>Chiloscyphus</i> sp.	(635)	
633	5 <i>β</i> -Hydroxy- <i>ent</i> - <i>β</i> -cyclogermacrene	C ₁₅ H ₂₂ O ₂		−94.9	Unidentified <i>Chiloscyphus</i> sp.	(635)	
634	(+)-Eudesma-3,11-dien-8 <i>α</i> -ol	C ₁₅ H ₂₄ O		+41.2	<i>Bazzania hochstetterii</i> <i>Bazzania spiralis</i>	(635) (490)	
635	(+)-6,11-Epoxyeudesmane	C ₁₅ H ₂₆ O			<i>Tritomaria polita</i> <i>Tritomaria polita</i>	(18) (18)	

636	(+)-6,7-Epoxyeudesm-3-ene	C ₁₅ H ₂₄ O			<i>Lophozia ventricosa</i>	(486)
637	(-)-6,7- <i>seco</i> -Eudesm-7(11)-en-6-ol	C ₁₅ H ₂₆ O			<i>Tritomaria polita</i>	(18)
638	(+)-Eudesm-11-en-6 β -ol	C ₁₅ H ₂₆ O			<i>Tritomaria polita</i>	(18)
639	(+)-Eudesm-11-en-6 α -ol	C ₁₅ H ₂₆ O			<i>Tritomaria polita</i>	(116)
640	Eudesma-5,11-dien-1 β -ol	C ₁₅ H ₂₂ O		-10.5	<i>Adelanthus lindenbergianus</i>	(615)
641	(1S*,4S*,7S*,10R*)-Eudesma-5,11-dien-1-ol	C ₁₅ H ₂₂ O		-167.7	<i>Gackstroemia</i> sp.	
642	1 β ,11-Dihydroxyeudesm-5-ene	C ₁₅ H ₂₆ O ₂		-21.5	<i>Adelanthus lindenbergianus</i>	(116)
643	1 β -Hydroxy-11-methoxyeudesm-5-ene	C ₁₆ H ₂₈ O ₂		-53.6	<i>Adelanthus lindenbergianus</i>	(116)
644	3 α -Hydroperoxyeudesm-4(14)-ene-6 β ,7 α -diol	C ₁₅ H ₂₆ O ₄			<i>Chiloscyphus polyanthos</i>	(498)
645	Eudesm-4-ene-3 α ,6 α ,7 α -triol	C ₁₅ H ₂₆ O ₃			<i>Chiloscyphus polyanthos</i>	(498)
646	2 β ,15-Diacetoxy-8 β -hydroxyeudesm-3-en-13-oic acid	C ₁₉ H ₂₈ O ₇		-7.8	<i>Marsipidium epiphytum</i>	(635)
647	(+)-6 β -Acetoxycitranoxide	C ₁₇ H ₂₈ O ₃		+19	<i>Lepidozia vitrea</i>	(746)
648	5 α ,8 α -Peroxyeudesm-6-ene	C ₁₅ H ₂₄ O ₂		+39.0	<i>Chiloscyphus subporosus</i>	(606)
649	10-Methoxycarbonyl-5 β ,6 β -epoxy- <i>ent</i> -eudesma-4-(15),11-dien-12,8 β -olide	C ₁₅ H ₁₈ O ₂			<i>Plagioclition conjugatus</i>	(72)
650	10-Methoxycarbonyl- <i>ent</i> -eudesma-4(15),11-dien-12,8 β -olide	C ₁₆ H ₂₀ O ₄			<i>Plagioclition conjugatus</i>	(72)
651	Densilobolide-A	C ₁₇ H ₂₄ O ₄	105-107	+71.7	<i>Frullania densiloba</i>	(589)
652	Densilobolide-B	C ₁₇ H ₂₂ O ₄	133-134	-75.9	Unidentified <i>Frullania</i> sp.	(424)
653	α -Cyclocostunolide	C ₁₅ H ₂₀ O ₂			<i>Frullania densiloba</i>	(589)
					Unidentified <i>Frullania</i> sp.	(424)
					<i>Frullania tamarisci</i> subsp. <i>obscura</i>	(492)
	(-)- α -Cyclocostunolide	C ₁₅ H ₂₀ O ₂			<i>Frullania convoluta</i>	(226)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ / ° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
	(+)- α -Cyclocostunolide	C ₁₅ H ₂₀ O ₂			Unidentified <i>Frullania</i> sp.	(843)	
654	Rothin-A acetate	C ₁₇ H ₂₂ O ₄			Unidentified <i>Frullania</i> sp.	(843)	
655	(-)- <i>ent</i> -Dihydro- α -cyclocostunolide	C ₁₅ H ₂₂ O ₂	133-135	-92.5	<i>Frullania convoluta</i>	(226)	
656	β -Cyclocostunolide	C ₁₅ H ₂₀ O ₂			<i>Frullania densiloba</i>	(589)	
					<i>Conocephalum japonicum</i>	(493)	
					<i>Frullania chevalieri</i>	(78)	
					<i>Frullania tamarisci</i> subsp. <i>obscura</i>	(492)	
657	Dihydro- β -cyclocostunolide	C ₁₅ H ₂₂ O ₂			<i>Frullania chevalieri</i>	(78)	
658	Frullanolide	C ₁₅ H ₂₀ O ₂			<i>Frullania congesta</i>	(78)	
					<i>Frullania incumbens</i>	(78)	
					<i>Frullania probosciphora</i>	(78)	
					<i>Frullania serrata</i>	(490)	
					<i>Plagiocchia bifaria</i>	(277)	
659	(-)-Frullanolide (+)-Frullanolide [6 α ,7 α ,10 α -4,11 (13)-Eudesmadien-12,6-olide]	C ₁₅ H ₂₀ O ₂ C ₁₅ H ₂₀ O ₂	73-74	-106 +114.7	<i>Frullania nisqualensis</i> <i>Frullania brasiliensis</i>	(410) (98)	
					<i>Frullania muscicola</i>	(443)	
					<i>Frullania dilatata</i>	(578)	
660	Dihydrofrullanolide	C ₁₅ H ₂₂ O ₂			<i>Frullania congesta</i>	(78)	
					<i>Frullania incumbens</i>	(78)	
					<i>Frullania magellanica</i>	(78)	
					<i>Frullania probosciphora</i>	(78)	
					<i>Frullania serrata</i>	(490)	
661	(+)-Dihydrofrullanolide	C ₁₅ H ₂₂ O ₂			<i>Frullania brasiliensis</i>	(98)	
662	(+)-Brothenolide Nepalensolide A (+)-Nepalensolide A	C ₁₅ H ₂₀ O ₂ C ₁₅ H ₂₀ O ₂ C ₁₅ H ₂₀ O ₂			<i>Frullania convoluta</i> <i>Frullania brasiliensis</i> <i>Frullania convoluta</i>	(226) (98) (226)	

Number	Compound	Formula	mp, °C	Ref.
663	(+)-Nepalensolide B	C ₁₅ H ₂₂ O ₂		(226)
664	Nepalensolide C	C ₁₅ H ₂₂ O ₂		(98)
665	5 α ,6 α ,7 α ,10 α -Eudesma-4(15),11-(13)-dien-12,6-olide	C ₁₅ H ₂₀ O ₂	+97.9	(443)
666	5 α ,6 α ,7 α ,10 α ,11 β ,13-Dihydro-eudesm-4(15)-en-12,6-olide	C ₁₅ H ₂₂ O ₂	+30.8	(443)
667	Citronillide [5 α ,6 α ,7 α ,10 β -Eudesma-4(15),11(13)-dien-12,6-olide]	C ₁₅ H ₂₀ O ₂	+140.3	(578) (443)
668	6 α -Hydroxyeudesm-4(15),11-(13)-dien-12-al	C ₁₅ H ₂₂ O ₂	+28	(886)
669	4 α ,6 α -Dihydroxyeudesm-11(13)-en-12-al	C ₁₅ H ₂₄ O ₃	-15.9	(886)
670	4- <i>epi</i> -Arbusculin A	C ₁₅ H ₂₄ O ₃	+47 148-149	(886) (492) (443)
671	(+)-Arbusculin B [6 α ,7 β ,10 β -Eudesma-4,11(13)-dien-12,6-olide]	C ₁₅ H ₂₀ O ₂	+26.2	
672	(-)- <i>ent</i> -Arbusculin B		-97	(92)
673	Dimer of 4 α ,6 α -Dihydroxyeudesm-11(13)-en-12-al with 4- <i>epi</i> -Arbusculin A	C ₃₀ H ₄₄ O ₅	+2.8	(886)
674	Muscicolide A	C ₃₀ H ₄₂ O ₅	+94.8	(443)
675	Muscicolide B	C ₃₀ H ₄₂ O ₅	+32.5	(443)
676	Diplophyllin	C ₁₅ H ₂₀ O ₂		(139) (15) (569)
	<i>ent</i> -Diplophyllin	C ₁₅ H ₂₀ O ₂	-79.4	(425)
677	<i>ent</i> -Dihydrodiplophyllin	C ₁₅ H ₂₂ O ₂		(15)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
678	<i>ent</i> -Diplophyllolide [(–)-eudesma-4,11(13)-dien-12,8-olide]	$\text{C}_{15}\text{H}_{20}\text{O}_2$		–110.4	<i>Marsupella alpina</i>	(17)	
					<i>Trocholejeunea sandvicensis</i>	(492)	
					<i>Diplophyllum albicans</i>	(15)	
					<i>Lophocolea bidentata</i>	(679)	
					<i>Mastigophora dielados</i>	(425)	
679	Isoalantolactone	$\text{C}_{15}\text{H}_{20}\text{O}_2$			<i>Marsupella alpina</i>	(17)	
					<i>Tritomaria quinqueidentata</i>	(928)	
					<i>Tritomaria quinqueidentata</i>	(928)	
					<i>Frullania dilatata</i>	(578)	
					<i>Frullania dilatata</i>	(578)	
					<i>Frullania dilatata</i>	(578)	
					<i>Asterella</i> sp. (?)	(71)	
					<i>Cephalozia recurvifolia</i>	(955)	
					<i>Dumortiera hirsuta</i>	(707)	
					<i>Frullania pycnantha</i>	(78)	
680	Spirodilatanolide A	$\text{C}_{15}\text{H}_{20}\text{O}_2$	65–67	+241.5	<i>Frullania spinifera</i>	(78)	
681	Spirodilatanolide B	$\text{C}_{15}\text{H}_{22}\text{O}_2$	48–50	+164.0	<i>Gymnocolea inflata</i>	(882)	
682	Spirodilatanolide C	$\text{C}_{15}\text{H}_{20}\text{O}_2$		+314.8	<i>Jungernannia fusiformis</i>	(882)	
683	(E)- β -Farnesene	$\text{C}_{15}\text{H}_{24}$			<i>Jungernannia infusca</i>	(587)	
					<i>Metacalypogeia alternifolia</i>	(748)	
					<i>Odontoschisma denudatum</i>	(882)	
					<i>Pellia endiviifolia</i>	(492)	
					<i>Porella epiphylla</i>	(492)	
					<i>Porella navicularis</i>	(143)	
					<i>Radula aquilegia</i>	(223)	
					<i>Radula carringtonii</i>	(223)	
					<i>Radula complanata</i>	(223)	

684	<i>(E,E)</i> - α -Farnesene	$C_{15}H_{24}$		<i>Radula jonesii</i>	(223)
				<i>Radula lindenbergiana</i>	(223)
				<i>Radula nudicaulis</i>	(223)
				<i>Radula wichurae</i>	(223)
				<i>Plagiochila maderensis</i>	(221)
				<i>Plagiochila retrorsa</i>	(221)
				<i>Plagiochila stricta</i>	(221)
				<i>Radula aquilegia</i>	(223)
				<i>Radula lindenbergiana</i>	(223)
				<i>Radula wichurae</i>	(223)
685	<i>(E,Z)</i> - α -Farnesene	$C_{15}H_{24}$		<i>Dumortiera hirsuta</i>	(492)
				<i>Frullania spinifera</i>	(78)
				<i>Gackstroemia decipiens</i>	(251)
				<i>Corsinia coriandrina</i>	(79)
686	3-Acetoxy-7,11-dihydroxyfarnesa-1,5,9-triene	$C_{17}H_{28}O_4$	+5	<i>Lunularia cruciata</i>	(921)
				<i>Jamesoniella tasmanica</i>	(79)
				<i>Plagiochila ovalifolia</i>	(72)
				Unidentified <i>Frullania</i> sp.	(872)
687	<i>(E)</i> -Nerolidol	$C_{15}H_{26}O$			(84)
					(843)
				<i>Frullania fragilifolia</i>	(644)
				<i>Frullania inflata</i>	(893)
688	3-(4,8-Dimethyl)-3,7-nonadienyl)-2-en-1,4-olide	$C_{15}H_{22}O_2$		<i>Frullania tamarisci</i>	(644)
				<i>Lepidozia reptans</i>	(681)
				<i>Lepidozia vitrea</i>	(645)
				<i>Lophozia ventricosa</i>	(486)
689	Germacrene A	$C_{15}H_{24}$		<i>Preissia quadrata</i>	(74)
					(433)
690	Germacrene B	$C_{15}H_{24}$			

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
691	Germacrene C	$\text{C}_{15}\text{H}_{24}$			<i>Preissia quadrata</i>	(433)	
692	Germacrene D	$\text{C}_{15}\text{H}_{24}$			<i>Calypogeia muelleriana</i>	(933)	
					<i>Conocephalum conicum</i>	(492)	
						(493)	
					<i>Chiloscyphus coarctatus</i>	(72)	
					<i>Drepanolejeunea</i>	(247)	
					<i>madagascariensis</i>		
					<i>Dumortiera hirsuta</i>	(492)	
					<i>Frullania ptychantha</i>	(78)	
					Unidentified <i>Jungermannia</i> sp.	(494)	
					<i>Kurzia makinoana</i>	(882)	
					<i>Lejeunea parva</i>	(882)	
					<i>Lepidolaena clavigera</i>	(72)	
					<i>Marchantia tosona</i>	(492)	
					<i>Mylia nuda</i>	(922)	
					<i>Mylia taylorii</i>	(922)	
					<i>Plagiochila atlantica</i>	(691)	
					<i>Plagiochila bifaria</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Porella canariensis</i>	(179)	
					<i>Preissia quadrata</i>	(74)	
					<i>Riccardia palmata</i>	(882)	
					<i>Trichocolea mollissima</i>	(72)	
				+243.5	<i>Jackiella javanica</i>	(587)	
	(+)-Germacrene D	$\text{C}_{15}\text{H}_{24}$			<i>Preissia quadrata</i>	(433)	

693	(+)-Isogermacrene A	C ₁₅ H ₂₄		<i>Saccogyna viticulosa</i>	(276)
694	Isogermacrene D	C ₁₅ H ₂₄		Unidentified <i>Jungermannia</i> sp.	(494)
695	(+)-Helminthogermacrene	C ₁₅ H ₂₄		<i>Trocholejeunea sandvicensis</i>	(492)
696	(1 <i>S</i> ,7 <i>R</i>)-Germacre-4(15),5,10(14)-trien-1-ol	C ₁₅ H ₂₄ O	-108.4	<i>Scapania undulata</i>	(16)
697	(1 <i>R</i> ,7 <i>R</i>)-Germacre-4(15),5,10(14)-trien-1-ol	C ₁₅ H ₂₄ O	+146.3	<i>Barbilophozia floerkei</i>	(583)
698	(4 <i>S</i> ,7 <i>R</i>)-Germacre-(1(10) <i>E</i> ,5 <i>E</i>)-dien-11-ol	C ₁₅ H ₂₆ O		<i>Jackiella javanica</i>	(587)
				<i>Bryopteris filicina</i>	(614)
				<i>Conocephalum conicum</i>	(604)
					(492)
					(543)
					(880)
				<i>Conocephalum japonicum</i>	(84)
				<i>Dumortiera hirsuta</i>	(492)
					(876)
					X-ray
699	Germacre-(1(10) <i>E</i> ,5 <i>E</i>)-dien-11-yl lunularate	C ₃₀ H ₃₈ O ₄	-46.5	<i>Frullania prychantha</i>	(78)
700	Germacre-1(10),5,11-triene	C ₁₅ H ₂₄		<i>Marchantia emarginata</i> subsp. <i>tosana</i>	(347)
701	1(10),5,11-Germacatrien-4 α -ol	C ₁₅ H ₂₄ O		<i>Marchantia emarginata</i> subsp. <i>tosana</i>	(347)
702	1(10),5-Germacadien-4 β -ol	C ₁₅ H ₂₆ O	-20.0	<i>Byopteris filicina</i>	(604)
				<i>Porella canariensis</i>	(179)
				<i>Asterella echinella</i>	(492)
				<i>Conocephalum conicum</i>	(492)
				<i>Conocephalum japonicum</i>	(492)
				<i>Dumortiera hirsuta</i>	(492)
				<i>Porella swartziana</i>	(848)
				<i>Wiesnerella denudata</i>	(492)
703	1(10),4-Germacadien-6 α -ol	C ₁₅ H ₂₆ O		Unidentified <i>Jungermannia</i> sp.	(494)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ °cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
704	Germacrastartianin	C ₁₅ H ₂₄ O ₂	77-80	-92.5	<i>Porella swartziana</i>	(848)	X-ray
705	8,15-Acetylsalomonitenolide	C ₁₉ H ₂₄ O ₆		+70	<i>Targonia lorbeeriana</i>	(620)	
706	8-Acetylsalomonitenolide	C ₁₇ H ₂₂ O ₅		+66	<i>Targonia lorbeeriana</i>	(620)	
707	8β-Acetoxydihydroparthenolide	C ₁₇ H ₂₄ O ₅		-45.1	<i>Frullania inflata</i>	(893)	
708	epi-Isocostunolide	C ₁₅ H ₂₀ O ₂		-56	<i>Frullania convoluta</i>	(226)	
709	Costunolide	C ₁₅ H ₂₀ O ₂	102-104	+117	<i>Conocephalum japonicum</i>	(493)	
					<i>Frullania lobulata</i>	(78)	
					<i>Frullania nissqualensis</i>	(410)	
					Unidentified <i>Frullania</i> sp.	(424)	
					<i>Wiesnerella denudata</i>	(426)	
						(490)	
710	(-)-ent-Costunolide	C ₁₅ H ₂₀ O ₂		-127	<i>Hepatosolonophora paucistipula</i>	(893)	
						(92)	
711	Dihydrocostunolide	C ₁₅ H ₂₂ O ₂			<i>Conocephalum japonicum</i>	(493)	
712	Tulipinolide	C ₁₇ H ₂₂ O ₄			<i>Frullania serrata</i>	(424)	
						(490)	
						(893)	
713	Dihydrotulipinolide	C ₁₇ H ₂₄ O ₄			Unidentified <i>Frullania</i> sp.	(426)	
					<i>Wiesnerella denudata</i>	(490)	
					<i>Frullania serrata</i>	(490)	
					<i>Wiesnerella denudata</i>	(490)	
714	4α,5β-Epoxy-8-epi-inunolide	C ₁₅ H ₂₀ O ₃			<i>Porella acutifolia</i> subsp. <i>tosana</i>	(315)	
715	1α-Hydroperoxy-4α,5β-epoxy-germacra-10(14),11(13)-dien-12,8α-olide	C ₁₅ H ₂₀ O ₅			<i>Porella perrottetiana</i>	(426)	
					<i>Porella acutifolia</i> subsp. <i>tosana</i>	(865)	

716	1 β -Hydroperoxy-4 α ,5 β -epoxy-germaera-10(14),11(13)-dien-12,8 α -olide	C ₁₅ H ₂₀ O ₅	<i>Porella acutifolia</i> subsp. <i>tosana</i>	(865)
717	(+)- α -Gorgonene	C ₁₅ H ₂₄	<i>Saccogyna viticulosa</i>	(276)
718	β -Gorgonene	C ₁₅ H ₂₄	<i>Saccogyna viticulosa</i>	(276)
719	Gorgona-1,4(15),11-triene	C ₁₅ H ₂₂	<i>Saccogyna viticulosa</i>	(276)
720	(-)-Gorgon-11-en-4-ol	C ₁₅ H ₂₆ O	<i>Saccogyna viticulosa</i>	(276)
721	1,5-Cyclo-3,6-gorgonadien-15,11-olide	C ₁₅ H ₁₈ O ₂	<i>Lepidozia spinosissima</i>	(611)
722	Maalioloxide	C ₁₅ H ₂₆ O	<i>Saccogyna viticulosa</i>	(276)
723	(-)-Maalioloxide	C ₁₅ H ₂₆ O	<i>Lophozia ventricosa</i>	(486)
	α -Guaiene	C ₁₅ H ₂₄	<i>Dumortiera hirsuta</i>	(707)
			<i>Frullania anomala</i>	(78)
			<i>Plagiochila suborbiculata</i>	(72)
			<i>Riccardia eriocaula</i>	(72)
			<i>Schistochila balfouriana</i>	(72)
			<i>Schistochila replata</i>	(72)
724	β -Guaiene	C ₁₅ H ₂₄	<i>Frullania inflata</i>	(893)
			<i>Plagiochila suborbiculata</i>	(72)
			<i>Porella perrattetiana</i>	(424)
			<i>Preissia quadrata</i>	(433)
725	Alismol [1 β ,5 α -guaia-6,10(15)-dien-4-ol]	C ₁₅ H ₂₆ O		
726	4,5- <i>seco</i> -Guaiane	C ₁₅ H ₂₄ O ₃	<i>Pellia epiphylla</i>	(176)
727	(+)-(1S*,5S*,7S*)-Guai-3,10(14)-dien-5,11-oxide	C ₁₅ H ₂₂ O	<i>Mylia nuda</i>	(922)
			<i>Mylia taylorii</i>	(922)
728	(-)-(1S*,5S*,7S*)-Guai-3,9-dien-5,11-oxide	C ₁₅ H ₂₂ O	<i>Mylia nuda</i>	(922)
			<i>Mylia taylorii</i>	(922)
729	(-)-Isoguaiene	C ₁₅ H ₂₄	<i>Dumortiera hirsuta</i>	(707)
730	<i>iso</i> - α -Gurjunene	C ₁₅ H ₂₄	<i>Pellia epiphylla</i>	(176)
731	γ -Gurjunene	C ₁₅ H ₂₄	<i>Frullania tamarisci</i>	(644)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p., °C	$[\alpha]_D^{25}$, °cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
732	(-)- γ -Gurjunene	C ₁₅ H ₂₄			<i>Calypogeia muelleriana</i> <i>Conocephalum conicum</i> <i>Dumortiera hirsuta</i>	(933) (544) (707)	
733	(+)-Aciphyllene	C ₁₅ H ₂₄			<i>Calypogeia muelleriana</i>	(933)	
734	Guaia-1(5),6-diene Guaia-6,9-diene	C ₁₅ H ₂₄ C ₁₅ H ₂₄			<i>Drepanolejeunea</i> <i>madagascariensis</i>	(247)	
735	(+)-Guaia-6,9-diene Guaia-6,9-diene-4 β -ol	C ₁₅ H ₂₄ C ₁₅ H ₂₄ O			<i>Dumortiera hirsuta</i> <i>Dumortiera hirsuta</i>	(707) (424) (426)	
736	5-Guaien-11-ol (-)- <i>ent</i> -5-Guaien-11-ol	C ₁₅ H ₂₆ O C ₁₅ H ₂₆ O			Unidentified <i>Jungermannia</i> sp. <i>Lophozia ventricosa</i> <i>Lepidozia borneensis</i> Unidentified <i>Jungermannia</i> sp. <i>Lepidozia vitrea</i> <i>Bazzania trilobata</i> <i>Calypogeia muelleriana</i> <i>Conocephalum conicum</i> <i>Jackiella javanica</i> <i>Tritomaria quinqueidentata</i> <i>Heteroscyphus coditus</i>	(494) (486) (490) (494) (645) (930) (933) (544) (614) (928) (617)	
737	1 α ,3 α ,4 α ,11-Tetrahydroxy- guai-5-ene	C ₁₅ H ₂₆ O ₄		-16.0			
738	Guaiswartzianin A	C ₁₅ H ₂₄ O ₂		+23.4	<i>Porella swartziana</i>	(848)	
739	Guaiswartzianin B	C ₁₅ H ₂₄ O ₂		+33.2	<i>Porella swartziana</i>	(848)	
740	Zaluzanin C	C ₁₅ H ₁₈ O ₃			<i>Wiesnerella denudata</i>	(492)	
741	Zaluzanin D	C ₁₇ H ₂₀ O ₄			<i>Wiesnerella denudata</i>	(893) (492)	

742	8 α -Acetoxyzaluzanin C	C ₁₇ H ₃₀ O ₅			<i>Wiesnerella denudata</i>	(893)
743	8 α -Acetoxyzaluzanin D	C ₁₉ H ₃₂ O ₆			<i>Wiesnerella denudata</i>	(490) (492) (893)
744	Dehydrocostus lactone	C ₁₅ H ₁₈ O ₂	56-58	-9.7	<i>Targonia lorbeeriana</i>	(620)
745	Acetyltrifolucoside lactone	C ₁₇ H ₂₂ O ₄	153-154	-53.1	<i>Wiesnerella denudata</i>	(84)
746	11- α H-Dihydrodehydrocostus lactone	C ₁₅ H ₂₀ O ₂		+94	<i>Targonia lorbeeriana</i>	(620) (620)
747	Porelladiolide	C ₁₅ H ₁₆ O ₄			<i>Porella japonica</i>	(316)
748	Porelladiolide-3,4-epoxide	C ₁₅ H ₁₆ O ₅			<i>Porella japonica</i>	(316)
749	11- <i>epi</i> -Porelladiolide	C ₁₅ H ₁₆ O ₄			<i>Porella japonica</i>	(316)
750	11,13-Dehydroporelladiolide	C ₁₅ H ₁₄ O ₄			<i>Porella japonica</i>	(316)
751	Porellaolide	C ₁₅ H ₁₈ O ₃			<i>Bazzania involuta</i>	(72)
752	α -Himachalene	C ₁₅ H ₂₄			<i>Bazzania trilobata</i>	(930)
					Unidentified <i>Frullania</i> sp.	(424)
					<i>Makinoa crispata</i>	(492)
					<i>Marsupella emarginata</i>	(17)
					<i>Plagiochila bifaria</i>	(221)
					<i>Plagiochila retrorsa</i>	(221)
					<i>Plagiochila stricta</i>	(221)
					<i>Schistochila balfouriana</i>	(72)
					<i>Scapania undulata</i>	(16)
753	β -Himachalene	C ₁₅ H ₂₄			<i>Bazzania japonica</i>	(485)
					<i>Jungermannia truncata</i>	(601)
					<i>Lepidozia concinna</i>	(72)
					<i>Metacalyptogeia cordifolia</i>	(882)
					<i>Mylia taylorii</i>	(922)
754	γ -Himachalene	C ₁₅ H ₂₄			<i>Plagiochila retrorsa</i>	(221)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ °cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
755	(+)-Himachala-1,3-diene	C ₁₅ H ₂₄			<i>Scapania undulata</i>	(16)	
756	6-Himachalen-9β-ol	C ₁₅ H ₂₆ O		+1	<i>Bazzania japonica</i>	(485)	
757	2-Himachalen-7β-ol	C ₁₅ H ₂₆ O			<i>Pellia epiphylla</i>	(176)	
758	Hodgsonox	C ₁₅ H ₂₂ O ₂			<i>Scapania undulata</i>	(16)	
					<i>Lepidolaena hodgsoniae</i>	(22)	
						(101)	
759	Hodgsonox B	C ₁₅ H ₂₄ O ₂		-1.4	<i>Lepidolaena hodgsoniae</i>	(101)	
760	Hodgsonox C	C ₁₅ H ₂₂ O ₃		+329	<i>Lepidolaena hodgsoniae</i>	(101)	
761	Hodgsonox D	C ₁₇ H ₂₆ O ₄		+25	<i>Lepidolaena hodgsoniae</i>	(101)	
762	Hodgsonox E	C ₁₅ H ₂₂ O ₂		-82	<i>Lepidolaena hodgsoniae</i>	(101)	
763	Hodgsonox F	C ₁₅ H ₂₂ O ₂		-25.3	<i>Lepidolaena hodgsoniae</i>	(101)	
764	Hodgsonox G	C ₁₅ H ₂₂ O ₂		+166	<i>Lepidolaena hodgsoniae</i>	(101)	
765	Hodgsonox H	C ₁₅ H ₂₂ O ₂		-164.6	<i>Lepidolaena hodgsoniae</i>	(101)	
766	α-Humulene	C ₁₅ H ₂₆			<i>Aneura alterniloba</i>	(72)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Chiloscyphus coarctatus</i>	(72)	
					<i>Dumortiera hirsuta</i>	(424)	
					<i>Frullania fragilifolia</i>	(644)	
					<i>Frullania media</i>	(78)	
					<i>Frullania tamarisci</i> subsp. <i>obscura</i>	(492)	
					<i>Marchantia pileata</i>	(72)	
					<i>Odontoschisma denudatum</i>	(882)	
					<i>Radula carringtonii</i>	(223)	
					<i>Radula complanata</i>	(223)	
					<i>Radula lindenbergiana</i>	(223)	
					<i>Radula wichurae</i>	(223)	

767	<i>iso-α</i> -Humulene	C ₁₅ H ₂₄			<i>Schistochila repleta</i>	(72)
768	<i>γ</i> -Humulene	C ₁₅ H ₂₆			<i>Wetsteinia schusterana</i>	(70)
768a	Humulene epoxide 2 (= 6,7-Epoxy-2,9-humuladiene)	C ₁₅ H ₂₆ O			<i>Saccogyna viticulosa</i>	(276)
					<i>Bazzania trilobata</i>	(930)
					<i>Dumortiera hirsuta</i>	(424)
769	(1 <i>E</i> ,3(15),6 <i>E</i>)-Humulatrien-10-ol	C ₁₅ H ₂₄ O	+139.7		<i>Bryopteris flicina</i>	(604)
770	2,6-Humuladien-10-ol	C ₁₅ H ₂₆ O	+10		<i>Pellia epiphylla</i>	(175)
771	1,6-Humuladien-10β-ol	C ₁₅ H ₂₆ O	+56.4 +63.7		<i>Conocephalum japonicum</i>	(84)
					<i>Marchantia emarginata</i> subsp. <i>tosana</i>	(896)
					<i>Tylimanthus tenellus</i>	(347)
772	(3-Hydroxy-5-oxo-4-phenyl-5 <i>H</i> -furan-2-ylidene)-phenylacetic acid 1,6-humuladien-10-yl ester	C ₃₃ H ₃₆ O ₅	+3.0	116	<i>Tylimanthus tenellus</i>	(896)
773	(3-Hydroxy-5-oxo-4-phenyl-5 <i>H</i> -furan-2-ylidene)-phenylacetic acid 6-hydroxy-1,7(11)-humuladien-10-yl ester	C ₃₃ H ₃₆ O ₆	-87.5		<i>Tylimanthus tenellus</i>	(896)
774	1,6-Humuladien-10β-yl lumularate	C ₃₀ H ₃₈ O ₄	-14.3		<i>Marchantia emarginata</i> subsp. <i>tosana</i>	(347)
775	1β,4β-Diacetoxylumen- <i>trans</i> -6,7-epoxide	C ₁₉ H ₃₀ O ₅	+11		<i>Bazzania tridens</i>	(959)
776	Bicyclohumulenone	C ₁₅ H ₂₄ O			<i>Plagiochila ovalifolia</i>	(701)
					<i>Plagiochila sciophila</i>	(492)
					<i>Radula perrottetii</i>	(492)
777	Longicyclene	C ₁₅ H ₂₄			<i>Metacalypogeia alternifolia</i>	(826)
						(748)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
778	Longifolene	$\text{C}_{15}\text{H}_{24}$			<i>Scapania undulata</i>	(16)	
					<i>Cuspidatula monodon</i>	(72)	
					<i>Dendromastigophora flagellifera</i>	(72)	
					<i>Frullania congesta</i>	(78)	
					<i>Herbertus sakuraii</i>	(323)	
						(365)	
779	Isolongifolene	$\text{C}_{15}\text{H}_{24}$			<i>Marsupella emarginata</i>	(17)	
					<i>Mastigophora dicladus</i>	(425)	
						(494)	
					<i>Metacalypogeia alternifolia</i>	(748)	
					<i>Riccardia nagasakiensis</i>	(141)	
					<i>Scapania undulata</i>	(16)	
780	β -Isolongibornene	$\text{C}_{15}\text{H}_{24}$			<i>Tylimanthus saccatus</i>	(72)	
					<i>Bryopteris flicina</i>	(604)	
					<i>Dendromastigophora flagellifera</i>	(72)	
781	(+)– β -Isolongibornene (–)-Longiborneol	$\text{C}_{15}\text{H}_{24}$ $\text{C}_{15}\text{H}_{26}\text{O}$			<i>Mastigophora dicladus</i>	(425)	
						(494)	
					<i>Scapania undulata</i>	(16)	
782	α -Longipinene	$\text{C}_{15}\text{H}_{24}$			<i>Scapania undulata</i>	(16)	
						(973)	
					<i>Bazzania trilobata</i>	(930)	
					<i>Makinoa crispata</i>	(492)	
					<i>Marsupella aquatica</i>	(19)	
					<i>Marsupella emarginata</i>	(17)	

783	β -Longipinene	$C_{15}H_{24}$	<i>Metacalypogeia alternifolia</i>	(748)
			<i>Plagiochila bifaria</i>	(277)
			<i>Scapania undulata</i>	(16)
			<i>Bazzania trilobata</i>	(930)
			<i>Cuspidatula monodon</i>	(72)
			<i>Dendromastigophora flagellifera</i>	(72)
			<i>Frullania atterrira</i> var. <i>lepida</i>	(78)
			<i>Frullania patula</i>	(78)
			<i>Frullania spinifera</i>	(78)
			<i>Lepidozia fauriana</i>	(645)
			<i>Metacalypogeia alternifolia</i>	(748)
			<i>Plagiochasma rupestre</i>	(97)
			Unidentified <i>Plagiochila</i> sp.	(701)
			<i>Scapania undulata</i>	(16)
784	(-)- β -Longipinene	$C_{15}H_{24}$	<i>Marsupella emarginata</i>	(17)
	(-)-Longipinanol	$C_{15}H_{26}O$	<i>Scapania undulata</i>	(16)
785	Marsupellone	$C_{15}H_{22}O$	<i>Marsupella emarginata</i>	(973)
			<i>Plagiochasma rupestre</i>	(17)
786	Marsupellol	$C_{15}H_{24}O$	<i>Marsupella emarginata</i>	(97)
	(-)-Marsupellol acetate	$C_{17}H_{26}O_2$	<i>Marsupella emarginata</i>	(17)
787	(-)-4- <i>epi</i> -Marsupellol	$C_{15}H_{24}O$	<i>Marsupella emarginata</i>	(17)
788	(-)-4- <i>epi</i> -Marsupellol acetate	$C_{17}H_{26}O_2$	<i>Marsupella emarginata</i>	(17)
789	(-)-5-Hydroxymarsupellol	$C_{17}H_{26}O_3$	<i>Marsupella emarginata</i>	(17)
790	Sativene	$C_{15}H_{24}$	<i>Metacalypogeia alternifolia</i>	(748)
791			<i>Notochorda confluenta</i>	(492)
			<i>Scapania undulata</i>	(16)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
792	Isosativene	$\text{C}_{15}\text{H}_{24}$			<i>Lepidozia fauriana</i>	(645)	
793	Cyclosativene	$\text{C}_{15}\text{H}_{24}$			<i>Dumortiera hirsuta</i>	(707)	
794	α -Maaliene	$\text{C}_{15}\text{H}_{24}$			<i>Calypogeia muelleriana</i>	(933)	
					<i>Plagiochila asplenoides</i>	(14)	
795	β -Maaliene	$\text{C}_{15}\text{H}_{24}$			<i>Apometzgeria pubescens</i>	(882)	
					<i>Scapania undulata</i>	(16)	
796	γ -Maaliene	$\text{C}_{15}\text{H}_{24}$			<i>Frullania solanderiana</i>	(78)	
					<i>Lepidozia fauriana</i>	(645)	
					<i>Mylia taylorii</i>	(922)	
					<i>Mylia nuda</i>	(922)	
					<i>Plagiochila asplenoides</i>	(14)	
						(604)	
					Unidentified <i>Plagiochila</i> sp.	(494)	
					<i>Radula perrottetii</i>	(826)	
797	(+)- γ -Maaliene	$\text{C}_{15}\text{H}_{24}$			<i>Calypogeia muelleriana</i>	(933)	
	Maali-1,3-diene	$\text{C}_{15}\text{H}_{22}$			<i>Diplrophyllum albicans</i>	(15)	
					<i>Plagiochila asplenoides</i>	(14)	
	(+)-Maali-1,3-diene	$\text{C}_{15}\text{H}_{22}$			<i>Calypogeia fissa</i>	(931)	
					<i>Calypogeia muelleriana</i>	(933)	
					<i>Bazzania japonica</i>	(485)	
					<i>Heteroscyphus coalitus</i>	(617)	
798	Maaliol	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Lepidozia fauriana</i>	(645)	
					<i>Lepidozia vitrea</i>	(645)	
					<i>Scapania undulata</i>	(16)	
					<i>Bazzania trilobata</i>	(930)	
	(-)-Maaliol	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Calypogeia muelleriana</i>	(933)	
					<i>Calypogeia fissa</i>	(931)	

799	(-)-4- <i>epi</i> -Maaliol	C ₁₅ H ₂₆ O			<i>Lophozia ventricosa</i>	(486)
800	Maalian-5-ol	C ₁₅ H ₂₆ O			<i>Plagiochila cristata</i>	(911)
					<i>Tritomaria quinqueidentata</i>	(928)
					<i>Plagiochila asplenoides</i>	(14)
					<i>Apometzgeria pubescens</i>	(882)
					<i>Lepidozia vitrea</i>	(871)
					<i>Plagiochila asplenoides</i>	(604)
					<i>Plagiochila ovalifolia</i>	(701)
801	(+)-Maalian-5-ol	C ₁₅ H ₂₆ O			<i>Plagiochila asplenoides</i>	(14)
802	<i>ent</i> -1 α -Hydroxy-3-maaliene	C ₁₅ H ₂₄ O	105-106	-84.6	<i>Leptoscyphus jackii</i>	(893)
	<i>ent</i> -1 β -Hydroxy-3-maaliene	C ₁₅ H ₂₄ O		-17.2	<i>Chiloscyphus mittianus</i>	(347)
					<i>Heteroscyphus</i> sp.	(635)
803	Maali-4(15)- <i>en</i> -1-ol	C ₁₅ H ₂₄ O			<i>Kurzia trichoclados</i>	(922)
					<i>Mylia taylorii</i>	(922)
					<i>Mylia nuda</i>	(922)
					<i>Mylia taylorii</i>	(569)
804	(+)- <i>ent</i> -Maali-4(15)- <i>en</i> -1 β -ol	C ₁₅ H ₂₄ O			<i>Lepidozia spinosissima</i>	(72)
	3 α -Acetoxy- <i>ent</i> -maalian-4 β -ol	C ₁₇ H ₂₈ O ₃				(611)
805	β -Monocyclonerolidol	C ₁₅ H ₂₆ O			<i>Archilejeunea olivacea</i>	(616)
806	Dehydro- β -monocyclonerolidol	C ₁₅ H ₂₄		+9.5	<i>Porella subobtusata</i>	(879)
					<i>Porella perrattetiana</i>	(581)
807	8-Hydroxy-9-methoxy- β -monocyclo-nerolidol	C ₁₆ H ₂₈ O ₂		+62.7	<i>Porella subobtusata</i>	(424)
808	Striatene	C ₁₅ H ₂₄				(581)
					<i>Cheilolejeunea trifaria</i>	(309)
					<i>Frullania falciloba</i>	(78)
					<i>Frullania incumbens</i>	(72)
					Unidentified <i>Frullania</i> sp.	
					<i>Psychanthus striatus</i>	(320)
					<i>Schistochila glaucescens</i>	(72)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ ° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
809	Striatol	C ₁₅ H ₂₆ O			<i>Thysananthus anguiformis</i> <i>Cheilolejeunea trifaria</i> <i>Frullania deplanata</i> <i>Lophozia ventricosa</i> <i>Ptychanthus striatus</i>	(72) (309) (78) (486) (396) (957)	Cell culture
810	Striatenic acid	C ₁₅ H ₂₂ O ₂		+43.5	<i>Cheilolejeunea serpentina</i>	(854)	
811	Tridensenal	C ₁₅ H ₂₆ O ₆			<i>Bazzania tridens</i>	(846)	
812	(2Z,4E)-Abscissic acid	C ₁₅ H ₂₀ O ₃			<i>Marchantia polymorpha</i>	(467)	
813	(2E,4E)-Abscissic acid	C ₁₅ H ₂₀ O ₃			<i>Marchantia polymorpha</i>	(467)	
814	Mytlayl-4(12)-ene	C ₁₅ H ₂₄			<i>Kurzia trichoclados</i> <i>Mylia taylori</i> <i>Bazzania japonica</i> <i>Marsupella aquatica</i>	(922) (922) (485) (17) (19)	
815	Mytlayl-4-ene	C ₁₅ H ₂₄			<i>Kurzia trichoclados</i> <i>Mylia taylori</i>	(922) (922)	
816	(-)-Mytlayl-4-ene	C ₁₅ H ₂₄			<i>Marsupella aquatica</i>	(19)	
817	Mytlayl-4(12)-en-5-ol Mytlaylenol (mytlayl-4(12)-en-15-ol)	C ₁₅ H ₂₄ O C ₁₅ H ₂₄ O		-35.0	<i>Bazzania trilobata</i> <i>Mylia taylorii</i>	(582) (569) (922)	
818	Mytlayl-4(12)-enyl-2-caffeate	C ₂₄ H ₃₀ O ₄		+2.4	<i>Bazzania nitida</i>	(289)	
819	Cyclomytlaylane (= Tridensene)	C ₁₅ H ₂₄			<i>Bazzania japonica</i> <i>Bazzania trilobata</i> <i>Kurzia trichoclados</i> <i>Marsupella aquatica</i>	(485) (930) (922) (17) (19)	

820	Cyclomyltaylan-5 α -ol	C ₁₅ H ₂₄ O	+36.1 +33.7	<i>Mytilia taylori</i> <i>Platichila sciophila</i> <i>Reboulia hemisphaerica</i> <i>Reboulia hemisphaerica</i>	(922) (492) (492) (242) (492)	X-ray
821	Cyclomyltaylan-5 β -ol	C ₁₅ H ₂₄ O	-12.3	<i>Reboulia hemisphaerica</i>	(935)	
822	Cyclomyltaylane-1 β ,5 α -diol	C ₁₅ H ₂₄ O ₂	+29.7	<i>Reboulia hemisphaerica</i>	(242)	X-ray
823	12-Acetoxycyclomyltaylane-1 β ,5 α -diol	C ₁₇ H ₂₆ O ₄	+29.7	<i>Reboulia hemisphaerica</i>	(242)	X-ray
824	Cyclomyltaylenol	C ₁₅ H ₂₄ O		<i>Kurzia trichoclados</i> <i>Mytilia taylorii</i>	(922) (569)	
825	(1 <i>R</i> ,5 <i>R</i>)-Diacetoxycyclomyltaylan-10-one	C ₁₉ H ₂₆ O ₅	-23.2 -45.2	<i>Bazzania madagassa</i>	(922) (291)	X-ray
826	(5 <i>R</i>)-Acetoxy-(1 <i>R</i>)-hydroxycyclomyltaylan-10-one	C ₁₇ H ₂₄ O ₄	-63.2	<i>Bazzania madagassa</i>	(293)	
827	(1 <i>R</i> ,5 <i>R</i>)-Dihydroxycyclomyltaylan-10-one	C ₁₅ H ₂₂ O ₃	-11.5	<i>Bazzania madagassa</i>	(293)	
828	(5 <i>R</i>),10 β -Diacetoxycyclomyltaylan-9 β -ol	C ₁₉ H ₂₈ O ₅	+241	<i>Bazzania madagassa</i>	(293)	
829	(5 <i>R</i>),10 β ,13-Triacetoxycyclomyltaylan-9 β -ol	C ₂₁ H ₃₀ O ₇	+45.3	<i>Bazzania madagassa</i>	(293)	
830	(5 <i>R</i>),9 β ,13-Triacetoxycyclomyltaylan-10 β -ol	C ₂₁ H ₃₀ O ₇	+67.2	<i>Bazzania madagassa</i>	(293)	
831	Rebouladienol (= Rulepidanol)	C ₁₅ H ₂₄ O		<i>Reboulia hemisphaerica</i>	(889)	
832	1 β ,10 β -Epoxynardosin-7,11-diene	C ₁₅ H ₂₂ O		<i>Gacstroemia decipiens</i>	(251)	
833	(-)-Tamariscol	C ₁₅ H ₂₆ O		<i>Frullania tamarisci</i>	(644)	
834	(-)-Tamariscene	C ₁₅ H ₂₄		<i>Frullania fragilifolia</i>	(644)	

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
835	(-)-Pacifigorgia-1(9),10-diene	$\text{C}_{15}\text{H}_{24}$			<i>Frullania tamarisci</i>	(644)	
					<i>Frullania fragilifolia</i>	(644)	
836	Pacifigorgia-1,10-diene	$\text{C}_{15}\text{H}_{24}$			<i>Frullania tamarisci</i>	(644)	
	(-)-Pacifigorgia-1,10-diene	$\text{C}_{15}\text{H}_{24}$			<i>Noteroclada confluens</i>	(492)	
					<i>Frullania fragilifolia</i>	(644)	
837	Pacifigorgia-1(6),10-diene	$\text{C}_{15}\text{H}_{24}$			<i>Frullania tamarisci</i>	(644)	
	(-)-Pacifigorgia-1(6),10-diene	$\text{C}_{15}\text{H}_{24}$			<i>Noteroclada confluens</i>	(492)	
					<i>Frullania fragilifolia</i>	(644)	
838	(-)-Pacifigorgia-2,10-diene	$\text{C}_{15}\text{H}_{24}$			<i>Frullania tamarisci</i>	(644)	
839	(+)-Pacifigorgia-2(10),11-diene	$\text{C}_{15}\text{H}_{24}$			<i>Frullania fragilifolia</i>	(644)	
840	α -Pinguisene	$\text{C}_{15}\text{H}_{24}$			<i>Frullania tamarisci</i>	(644)	
					<i>Drepanolejeunea madagascariensis</i>	(247)	
					<i>Porella canariensis</i>	(179)	
					<i>Porella perrottetiana</i>	(424)	
					<i>Trocholejeunea sandvicensis</i>	(539)	
841	Pinguiseneol	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Bazzania novae-zelandiae</i>	(615)	
						(901)	
					<i>Porella canariensis</i>	(179)	
842	neo-Pinguiseneol	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Porella vernicosa</i>	(637)	
843	β -Pinguisenediol	$\text{C}_{15}\text{H}_{22}\text{O}_2$		-33.3	<i>Dicranolejeunea yoshinagana</i>	(869)	
					<i>Porella platyphylla</i>	(138)	

844	Methyl 2 α -hydroxy-6-oxo-11-pinguisanoate	C ₁₆ H ₂₆ O ₄			<i>Porella platyphylla</i>	(138)
845	Naviculol	C ₁₃ H ₂₆ O	+44		<i>Bazzania novae-zelandiae</i>	(145) (615) (901)
846	Naviculyl caffeate	C ₂₄ H ₃₂ O ₄	+28		<i>Porella navicularis</i>	(143)
847	5-Pinguisen-11-ol	C ₁₃ H ₂₆ O	+21		<i>Bazzania novae-zelandiae</i>	(145)
848	7-Keto-8-carbomethoxypinguisenol	C ₁₆ H ₂₄ O ₄			<i>Porella navicularis</i>	(901)
					<i>Porella acutifolia</i> subsp. <i>tosana</i>	(143) (315) (322)
					<i>Porella canariensis</i>	(179)
					<i>Porella perrattetiana</i>	(424)
						(426)
849	Acutifolone A	C ₁₆ H ₂₂ O ₃	102-104	+2.08	<i>Porella acutifolia</i> subsp. <i>tosana</i>	(315) (316) (322)
850	Acutifolone B	C ₁₆ H ₂₀ O ₃	138-140	-94.9	<i>Porella perrattetiana</i>	(424)
					<i>Porella acutifolia</i> subsp. <i>tosana</i>	(315) (316) (322)
						X-ray
851	Lejeuneapinguisenone	C ₁₃ H ₂₂ O ₂			<i>Porella perrattetiana</i>	(424)
852	Lejeuneapinguisanolide	C ₁₃ H ₂₂ O ₄	180-197	+23	<i>Trocholejeunea sandvicensis</i>	(460)
853	Porellapinguisanolide	C ₁₃ H ₂₂ O ₅			<i>Trocholejeunea sandvicensis</i>	(460)
854	Bisacutifolone A	C ₃₂ H ₄₄ O ₇	204-206	+59.0	<i>Porella platyphylla</i>	(138)
					<i>Porella acutifolia</i> subsp. <i>tosana</i>	(315) (316) (322)
						X-ray

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
855	Bisacutifolone B	$\text{C}_{32}\text{H}_{44}\text{O}_7$		+18.1	<i>Porella acutifolia</i> subsp. <i>tosana</i>	(315)	
856	Bisacutifolone C	$\text{C}_{32}\text{H}_{44}\text{O}_6$		+69.5	<i>Porella acutifolia</i> subsp. <i>tosana</i>	(316)	
857	Pinguisone	$\text{C}_{13}\text{H}_{20}\text{O}_2$			<i>Aneura pinguis</i>	(322)	Axenic culture
858	15-Acetoxypinguisone	$\text{C}_{17}\text{H}_{24}\text{O}_3$			<i>Cryptothallus mirabilis</i>	(812)	
						(688)	
859	Dehydropinguisone	$\text{C}_{15}\text{H}_{18}\text{O}_2$	70–71	+209.2	<i>Plagiochila retrospectans</i>	(692)	
						(72)	X-ray
860	Norpinguisone	$\text{C}_{14}\text{H}_{18}\text{O}_2$			<i>Porella canariensis</i>	(579)	
						(179)	
						(604)	
					<i>Porella densifolia</i>	(669)	
					<i>Porella recurva</i>	(913)	
					<i>Porella vermicosa</i>	(637)	
861	Norpinguisone methyl ester	$\text{C}_{15}\text{H}_{18}\text{O}_4$			<i>Bryopteris flicina</i>	(576)	
						(604)	
					<i>Porella canariensis</i>	(179)	
					<i>Porella elegantula</i>	(72)	
					<i>Porella densifolia</i>	(669)	
					<i>Porella granditoba</i>	(814)	
					<i>Porella navicularis</i>	(143)	
					<i>Porella recurva</i>	(913)	
					<i>Porella vermicosa</i>	(637)	
862	Deoxopinguisone	$\text{C}_{13}\text{H}_{22}\text{O}$			<i>Porella canariensis</i>	(179)	
					<i>Porella elegantula</i>	(72)	
					<i>Porella vermicosa</i>	(637)	
					<i>Ptilidium ciliare</i>	(596)	

863	9-Formyldeoxopinguisone	$C_{15}H_{20}O_2$		<i>Trocholejeunea sandvicensis</i>	(492)
864	14-Acetoxydeoxopinguisone	$C_{17}H_{24}O_3$	-49.7	<i>Wetsteinia schusterana</i>	(70)
865	Deoxopinguisone-12-oic acid methyl ester	$C_{16}H_{22}O_3$	-70 -50.1	<i>Dicranolejeunea yoshinagana</i> <i>Dicranolejeunea yoshinagana</i> <i>Porella canariensis</i>	(869) (869) (179)
866	Deoxopinguisone-15-oic acid methyl ester	$C_{16}H_{22}O_3$		<i>Porella canariensis</i>	(179)
867	Pinguisene (= Dehydrodeoxopinguisone)	$C_{15}H_{20}O$		<i>Porella vernicosa</i>	(637)
868	Dehydrodinguisenol	$C_{15}H_{22}O_2$		<i>Trocholejeunea sandvicensis</i>	(492)
869	Furanopinguisanol	$C_{15}H_{20}O_2$		<i>Trocholejeunea sandvicensis</i>	(460)
870	Bryopteris A	$C_{16}H_{20}O_2$	-12.9	<i>Trocholejeunea sandvicensis</i>	(492)
871	Bryopteris B	$C_{17}H_{22}O_5$	-19.0	<i>Bryopteris flicina</i>	(460)
872	Bryopteris C	$C_{17}H_{22}O_6$	-44.5	<i>Bryopteris flicina</i>	(576)
873	Bryopteris D	$C_{15}H_{20}O$	+49.6	<i>Porella granditoba</i>	(814)
874	Pinguisanin	$C_{15}H_{20}O_2$		<i>Bryopteris flicina</i>	(576)
875	Dehydrodinguisanin	$C_{15}H_{18}O_2$		<i>Bryopteris flicina</i>	(604)
876	Ptychanolactone	$C_{15}H_{22}O_3$	-153.0	<i>Bryopteris flicina</i>	(576)
877	4 β -Carbomethoxy-6 α -methoxy-pinguis-11,6-olide	$C_{17}H_{24}O_5$	-156.7	<i>Porella platyphylla</i>	(138)
878	3-Oxopinguis-5(10),6-dien-11,6-olide	$C_{15}H_{20}O_4$	+106.0	<i>Phluidium ciliare</i>	(583)
879	6 α -Hydroxy-3-oxopinguis-5(10)-en-11,6-olide	$C_{15}H_{20}O_4$	-19.2	<i>Trocholejeunea sandvicensis</i>	(596)
				<i>Trocholejeunea sandvicensis</i>	(492)
				<i>Bryopteris flicina</i>	(604)
				<i>Porella canariensis</i>	(582)
				<i>Aneura pinguis</i>	(812)
				<i>Aneura pinguis</i>	(812)
					Axenic culture
					Axenic culture

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ °cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
880	6 α -Methoxy-3-oxopinguis-5(10)-en-11,6-olide	C ₁₆ H ₂₂ O ₄		-27.9	<i>Aneura pinguis</i>	(812)	Axenic culture
881	6,11-Epoxy-15-nor-3,4-dioxo-5,10-pinguisadien-12-acetate	C ₁₆ H ₁₈ O ₅			<i>Porella recurva</i> <i>Radula lindenbergiana</i> <i>Radula nudicaulis</i> <i>Porella recurva</i>	(913) (223) (223) (913)	
882	6,11-Epoxy-15-nor-4-oxo-5,10-pinguisadien-12-acetate	C ₁₆ H ₂₀ O ₄	102-103				
883	Grandilobalide A	C ₁₅ H ₁₈ O ₃		-84.0	<i>Porella grandiloba</i>	(814)	
884	Grandilobalide B	C ₁₅ H ₁₈ O ₅		-88.0	<i>Porella grandiloba</i>	(814)	
885	Grandilobalide C	C ₁₅ H ₁₉ O ₅		-93.3	<i>Porella grandiloba</i>	(814)	
886	6 α -Hydroxy-4,8-dimethoxycarbonyl-pinguis-11,6-olide	C ₁₇ H ₂₂ O ₇		-140.0	<i>Porella grandiloba</i>	(814)	
887	6 α -Methoxypinguis-5(10)-en-11,6-olide	C ₁₆ H ₂₄ O ₃		+68.2	<i>Porella navicularis</i>	(143)	
888	6 α -Methoxypinguis-5(10)-en-11,6-olide-15-carboxylic acid	C ₁₆ H ₂₂ O ₅		+82.1	<i>Porella navicularis</i>	(143)	
889	5 α ,10 α -Epoxyinguisane-11,6-olide-15-carboxylic acid	C ₁₆ H ₂₂ O ₅		+48.0	<i>Porella navicularis</i>	(143)	
890	methyl ester Ptychanolide	C ₁₅ H ₂₂ O ₃			<i>Porella canariensis</i> <i>Ptychanthus striatus</i> <i>Trocholejeunea sandvicensis</i> <i>Plagioclista dusenii</i>	(179) (957) (492) (32)	
891	α -Santalene	C ₁₅ H ₂₄			<i>Porella perrottetiana</i> <i>Porella subobtusata</i> <i>Radula complanata</i>	(424) (581) (223)	

892	β -Santalene	$C_{15}H_{24}$		<i>Marsupella alpina</i> <i>Porella navicularis</i> <i>Radula complanata</i> <i>Radula lindenbergiana</i> <i>Radula wichurae</i> <i>Porella subobiusa</i>	(17) (143) (223) (223) (223) (569) (581)
893	α -Santalol-(12S),13-diol	$C_{15}H_{26}O_2$			
894	β -Photosantalol A	$C_{15}H_{24}O$	-47	<i>Gackstroemia decipiens</i>	(252)
895	β -Photosantalol B	$C_{15}H_{24}O$	-88	<i>Gackstroemia decipiens</i>	(252)
896	9-Hydroxysantalol-2(14),11-diene	$C_{15}H_{24}O$	-77	<i>Gackstroemia decipiens</i>	(252)
897	11-Hydroxysantalol-2(14),8-diene	$C_{15}H_{24}O$	-24	<i>Gackstroemia decipiens</i>	(252)
898	Hinesene	$C_{15}H_{24}$		<i>Frullania tamarisci</i> subsp. <i>obscura</i>	(492)
899	(+)-1(10)-Spirovetiven-7 β -ol	$C_{15}H_{26}O$	+21	Unidentified <i>Frullania</i> sp. <i>Calypogeia muelleriana</i> <i>Lepidozia reptans</i> <i>Lophozia ventricosa</i> <i>Lepidozia reptans</i> <i>Bazzania trilobata</i> <i>Frullania falciloba</i>	(843) (933) (681) (486) (681) (930) (78)
900	Spirovetiva-1(10),7(11)-diene	$C_{15}H_{22}$		Unidentified <i>Frullania</i> sp.	(424)
901	<i>ent</i> -Thujopsene	$C_{15}H_{24}$		<i>Lepidozia fauriana</i> <i>Marchantia polymorpha</i> <i>Marsupella emarginata</i> <i>Radula perrottetii</i>	(645) (492) (17) (492)
902	<i>ent</i> -Thujopsan-7 β -ol	$C_{15}H_{26}O$		<i>Symphogyna brasiliensis</i>	(492)
903	Thujopsan-7 β -ol	$C_{15}H_{26}O$	-5.5	<i>Trocholejeunea sandvicensis</i> <i>Marchantia polymorpha</i> <i>Jungermannia infusca</i>	(539) (492) (595)

(continued)

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}10^{-1}$	Plant source(s)	Reference(s)	Comments
904	<i>ent</i> -Thuiopsenone (= Thuiops-3-en-5-one)	$\text{C}_{15}\text{H}_{22}\text{O}$			<i>Marchantia polymorpha</i>	(492)	
905	7(11)-Thuiopsen-3 α -ol	$\text{C}_{15}\text{H}_{24}\text{O}$	47–48.5		<i>Reboulia hemisphaerica</i>	(436)	
906	Trifarienol A	$\text{C}_{15}\text{H}_{26}\text{O}_2$	59–60	+10.2	<i>Cheilolejeunea trifaria</i>	(889) (306) (309)	X-ray
907	Trifarienol B	$\text{C}_{15}\text{H}_{26}\text{O}_2$	105–105.5	–3.6	<i>Cheilolejeunea trifaria</i>	(306) (309)	
908	Trifarienol C	$\text{C}_{17}\text{H}_{28}\text{O}_3$	99–100	+13.0	<i>Plagiochila terebrans</i>	(295)	
909	Trifarienol D	$\text{C}_{17}\text{H}_{28}\text{O}_3$	83–85	–0.24	<i>Cheilolejeunea trifaria</i>	(309)	
910	Trifarienol E	$\text{C}_{15}\text{H}_{24}\text{O}_2$		+2.4	<i>Cheilolejeunea trifaria</i>	(309)	
911	(–)-Trifara-9,14-diene	$\text{C}_{15}\text{H}_{24}$			<i>Trocholejeunea sandvicensis</i>	(539)	
912	(–)-3,7-diepi-Trifara-9,14-diene	$\text{C}_{15}\text{H}_{24}$			<i>Trocholejeunea sandvicensis</i>	(539)	
913	(+)-Neotrifariadiene	$\text{C}_{15}\text{H}_{24}$			<i>Trocholejeunea sandvicensis</i>	(539)	
914	Presilphiperfolan-1-ol	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Conocephalum conicum</i>	(543)	
915	Kelosoene (= Tritomarene)	$\text{C}_{15}\text{H}_{24}$			<i>Barbilophozia floerkei</i>	(15)	
					<i>Calypogeia muelleriana</i>	(933)	
					<i>Diplophyllum albicans</i>	(15)	
					<i>Kurzia trichoclados</i>	(922)	
					<i>Mylia taylorii</i>	(922)	
					<i>Mylia nuda</i>	(922)	
					<i>Pellia endiviifolia</i>	(492)	
					<i>Ptychanthus striatus</i>	(320)	
					<i>Saccogyna viticulosa</i>	(396)	
					<i>Tritomaria quinqueidentata</i>	(276)	
916	α -Patchoulene	$\text{C}_{15}\text{H}_{24}$			<i>Mastigophora dictados</i>	(928) (425) (494)	

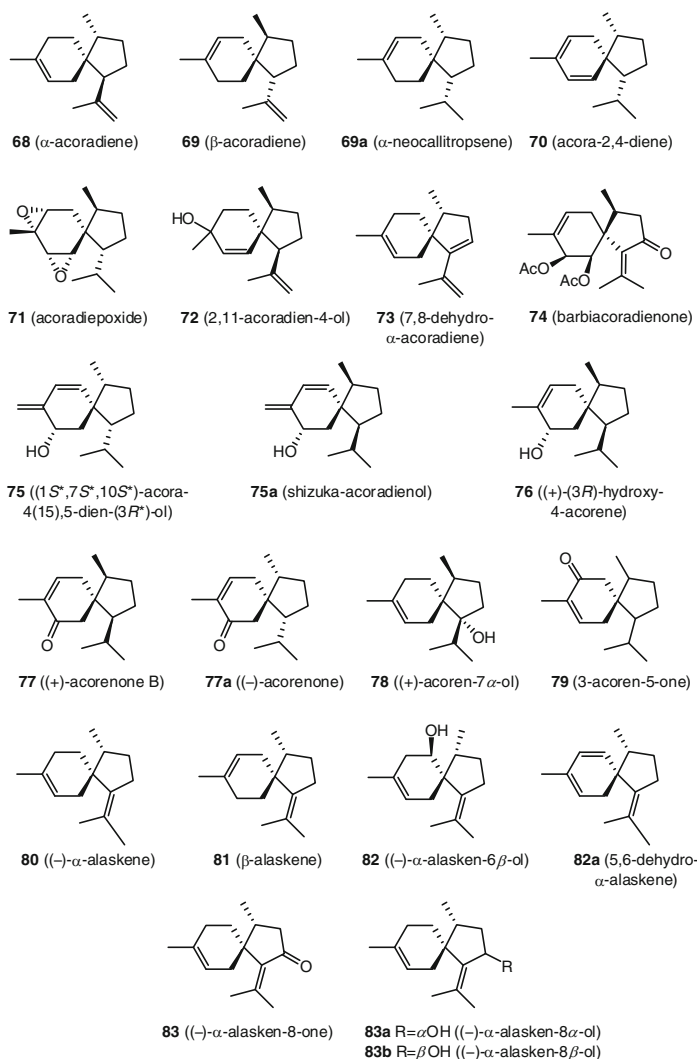
917	(+)-Chenopodene	C ₁₅ H ₂₄	+32.7	<i>Porella navicularis</i> (143)
918	(-)-Chenolodanol	C ₁₅ H ₂₆ O		<i>Marchantia chenopoda</i> (840)
919	(+)-Sandvicene	C ₁₅ H ₂₄	-59.1	<i>Porella perrattetiana</i> (424)
				<i>Marchantia chenopoda</i> (849)
				<i>Trocholejeunea sandvicensis</i> (539)
				Unidentified <i>Frullania</i> sp. (424)
				<i>Porella perrattetii</i> (424)
920	2 α -Hydroxygackstr-9-ene	C ₁₅ H ₂₄ O		<i>Gackstroemia</i> sp. (615)
921	Italicene	C ₁₅ H ₂₄		<i>Plagiochila asplenoides</i> (14)
922	β -Funebrene	C ₁₅ H ₂₄		<i>Plagiochila asplenoides</i> (14)
922a	β -Funebrene epoxide	C ₁₅ H ₂₄ O		Unidentified <i>Frullania</i> sp. (424)
923	β -Duprezianene	C ₁₅ H ₂₄		<i>Trocholejeunea sandvicensis</i> (539)
924	Riccardiophenol C	C ₂₁ H ₂₈ O ₂	+26	<i>Riccardia crassa</i> (651)
925	(+)-(4S,4aS,5R,8aS)- <i>trans</i> -4,8a-Dimethyl-4a,5-epoxydecalin	C ₁₂ H ₂₀ O	+55	<i>Lophocolea bidentata</i> (679)
926	Octalin	C ₁₂ H ₂₀		<i>Lophocolea heterophylla</i> (679)
927	Olivacene	C ₁₅ H ₂₂		<i>Lophocolea bidentata</i> (679)
928	Nudenoic acid	C ₁₅ H ₂₂ O ₂	-21	<i>Lophocolea heterophylla</i> (679)
				<i>Archilejeunea olivacea</i> (879)
				<i>Mylia nuda</i> (476)
929	Nudenal	C ₁₅ H ₂₂ O		<i>Mylia nuda</i> (922)
				<i>Mylia nuda</i> (476)
930	(-)- <i>ent</i> -Prelacinan-(7S)-ol	C ₁₅ H ₂₆ O	-4.9	<i>Jungermannia infusca</i> (922)
931	Glaucenolide	C ₁₅ H ₂₂ O ₃	+60	<i>Schistochila glaucescens</i> (600)
932	Sesquisabinene	C ₁₅ H ₂₄		<i>Schistochila glaucescens</i> (712)
				<i>Chandonanthus hirtellus</i> (490)
				<i>Frullania falciloba</i> (78)
				<i>Mannia fr-agrans</i> (542)
				<i>Plagiochila sciophila</i> (492)
				<i>Radula aquilegia</i> (223)

(continued)

X-ray

Table 4.2 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
933	Waitziacuminone	$\text{C}_{15}\text{H}_{24}\text{O}$			<i>Jamesoniella colorata</i>	(340)	
934	(-)-Perfora-1,7-diene	$\text{C}_{15}\text{H}_{24}$			<i>Scapania undulata</i>	(16)	
935	Valerena-4,7(11)-diene	$\text{C}_{15}\text{H}_{24}$			<i>Radula perrottetii</i>	(826)	
936	<i>ar</i> -Tenuifolene	$\text{C}_{15}\text{H}_{20}$			<i>Radula perrottetii</i>	(826)	
937	Zizaene	$\text{C}_{15}\text{H}_{24}$			<i>Pellia epiphylla</i>	(492)	
					<i>Radula aquilegia</i>	(223)	
					<i>Radula wichurae</i>	(223)	
938	Dactylol	$\text{C}_{15}\text{H}_{16}\text{O}_2$			<i>Makinoa crispata</i>	(492)	
					<i>Noteroclada confluens</i>	(492)	
939	<i>ent</i> -Dactylol	$\text{C}_{15}\text{H}_{16}\text{O}_2$			<i>Conocephalum conicum</i>	(543)	
	α -Isocomene	$\text{C}_{15}\text{H}_{24}$			<i>Noteroclada confluens</i>	(492)	
940	(-)-Ventricos-7(13)-ene	$\text{C}_{15}\text{H}_{24}$			<i>Lophozia ventricosa</i>	(486)	
941	Dihydro- β -agarofuran	$\text{C}_{15}\text{H}_{26}\text{O}$			<i>Symphyogyna brasiliensis</i>	(492)	
942	Pentalenene	$\text{C}_{15}\text{H}_{24}$			<i>Frullania serrata</i>	(490)	
					<i>Radula aquilegia</i>	(223)	
					<i>Radula carringtonii</i>	(223)	
					<i>Radula complanata</i>	(223)	
					<i>Radula holtii</i>	(223)	
					<i>Radula jonesii</i>	(223)	
					<i>Radula lindenbergiana</i>	(223)	
					<i>Radula nudicaulis</i>	(223)	
					<i>Radula wichurae</i>	(223)	
943	Silphin-1-ene	$\text{C}_{15}\text{H}_{24}$			<i>Frullania serrata</i>	(490)	
944	Petasitene	$\text{C}_{15}\text{H}_{24}$			<i>Radula aquilegia</i>	(223)	
					<i>Radula complanata</i>	(223)	
					<i>Radula lindenbergiana</i>	(223)	
					<i>Radula wichurae</i>	(223)	



Acorane-type sesquiterpenoids found in the Marchantiophyta

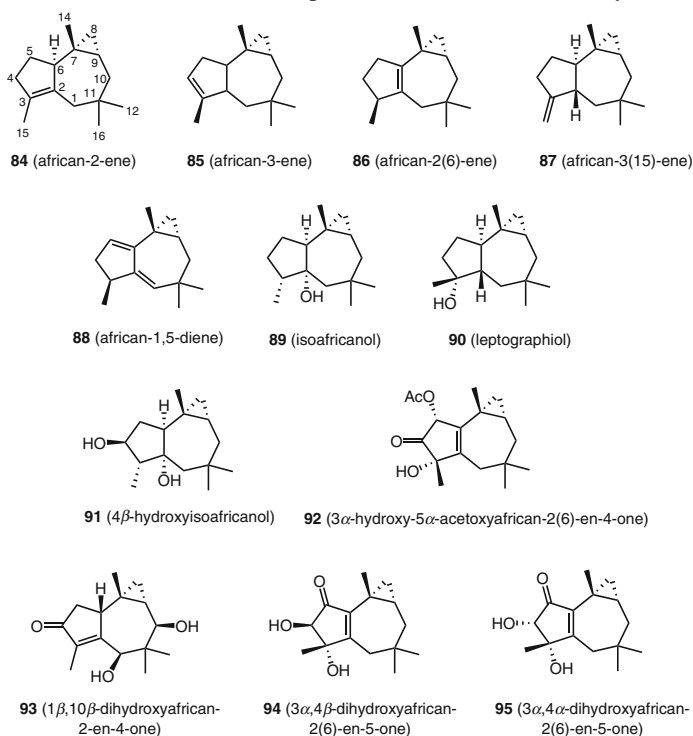
Fractionation of the ether extract of the Madagascan *Bazzania madagassa* resulted in the isolation of acora-2,4-diene (**70**) and a new acorane sesquiterpenoid, for which the relative structure was determined as (1*S**,7*S**,10*S**)-acora-4(15),5-diene-(3*R**)-ol (**75**) from its 2D-NMR spectra, and by comparison of its spectroscopic data with those of shizuka-acoradienol (**75a**) ([291](#)), isolated from the higher plant *Chloranthus japonicus* ([397](#)).

The ethyl acetate extract of the Taiwanese *Bazzania triedens* was purified by CC to give three acoranes, (+)-(1*R*,7*R*,10*R*)-4-acoren-3-one (= (+)-acorenone B) (**77**), (1*R*,7*S*,10*R*)-(+)-acoren-7 α -ol (**78**), and 3-acoren-5-one (**79**), of which compound **78** was new, with the dextro-enantiomer **77** obtained as a natural product for the first time ([951](#)). The spectroscopic data of **77** were identical to those of synthetic (+)-

acorenone B. (–)-Acorenone B (**77a**) is an uncommon essential oil component and found only from the higher plant *Bothriochloa intermedia* before (**532**). The structure of **78** was elucidated by analysis of its 2D-NMR data (COSY, HMQC, HMBC, and NOESY). Compound **79** has been isolated from several plant species previously (**161**).

4.2.2 *Africanes*

Africane-type sesquiterpenoids are relatively rare in Nature. Until 1995, 12 africane sesquiterpenoids had been found in liverworts (**40**). Subsequently, africane-3-ene (**85**) was detected in Canadian and Japanese *Herbertus aduncus* by GC/MS (**323**).

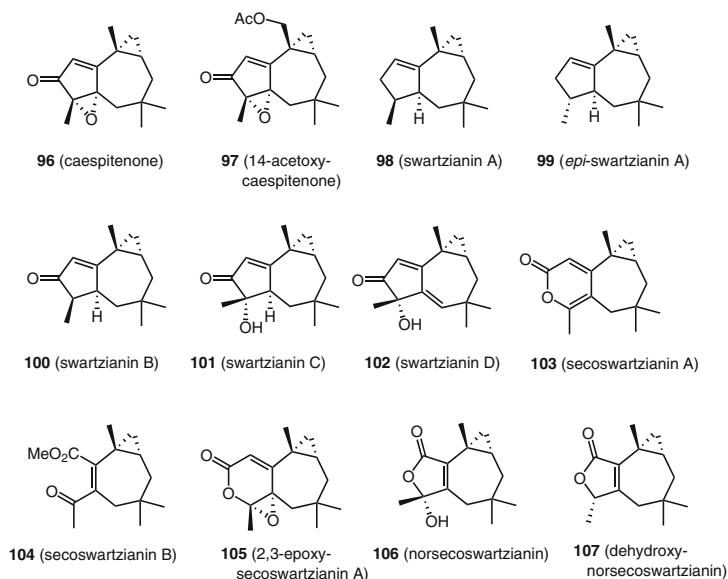


Africane-type sesquiterpenoids found in the Marchantiophyta

The ether extract of the gametophyte of European *Pellia epiphylla* was purified by CC and HPLC to yield 3(15)-africanene (**87**) (**391**) and the new *epi*-swartzianin A (**99**) (**176**). The sporophytes of the same species were shown to contain a new africane sesquiterpenoid, 4β-hydroxyisoafricanol (**91**), along with 3(15)-africanene (**87**), *epi*-swartzianin A (**99**), and isoafricanol (**89**), which was also obtained from the dichloromethane extract of the spores of the same liverwort along with leptographiol (**90**). Compound **91** showed very close similarities to isoafricanol (**89**) in its NMR spectra, indicating that this substance possesses an africane skeleton. The complete structure was deduced from the DEPT, COSY, NOESY, and other 2D-NMR spectra (**175**). *epi*-Swartzianin A (**99**) was isolated also from the higher plant, *Lippia integrifolia*, and its absolute configuration was found to be

the same as when purified from the liverwort *Pellia epiphylla* (149). Caespitenone (96) and secoswartzianin A (103) were also isolated from the ether extract of gametophytes of *Porella grandiloba* (814).

Isoafricanol (89) and leptographiol (90) were first obtained from an ascomycete, *Leptographium lundbergii* (4). Isoafricanol (89) has also been isolated from the liverwort, *Nardia scalaris* (40). A number of africanes and *seco*-africanes more complex than those found in *P. epiphylla*, were isolated from the South American *Porella swartziana* (848) and *P. caespitans* var. *setigera* (40).



African-, secoafrican-, and norsecoafriane-type sesquiterpenoids found in the Marchantiophyta

The ether extract of *Porella subobtusa* was purified by CC to afford a new african (97), together with the known africanes, caespitenone (96), swartzianin A (98), and secoswartzianin A (103) (40). The NMR spectra of 97 closely resembled those of caespitenone (96) and the whole structure was deduced as 14-acetoxycaespitenone from its 2D-NMR data. The absolute configuration of 97 was established by a negative Cotton effect (250 and 327 nm) in the CD spectrum, as observed in caespitenone (581).

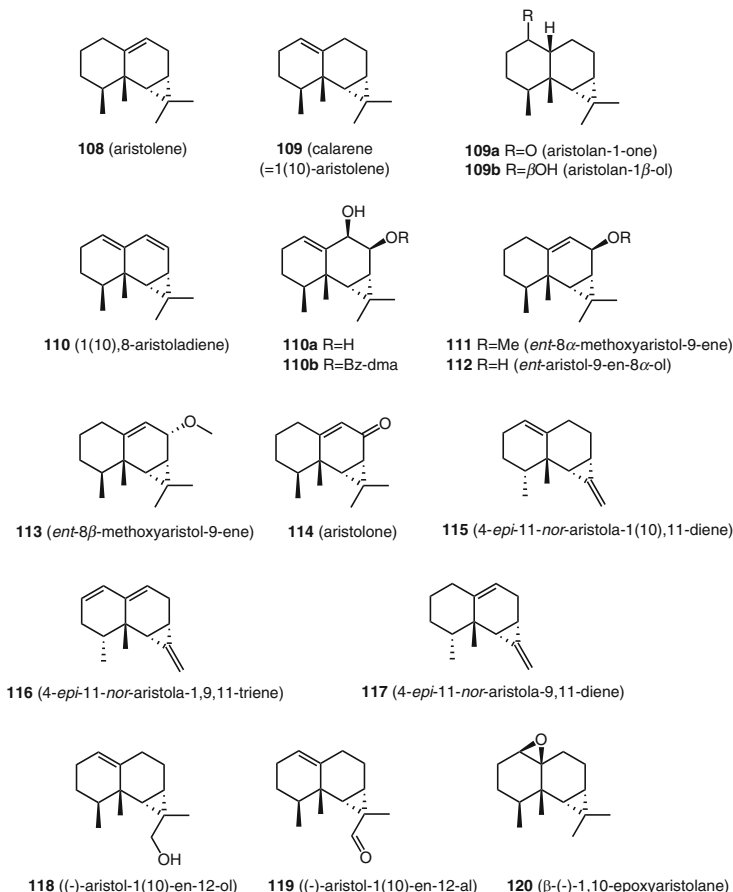
Porella swartziana is widespread in the rain forests of certain South American mountain ranges. The Colombian *Porella swartziana* is a rich source of african sesquiterpenoids (40). Besides caespitenone (96), swartzianins A-D (98, 100–102), secoswartzianins A (103) and B (104), and norsecoswartzianin (106) have been isolated and characterized structurally from this liverwort, together with the two known compounds, 3 α -hydroxy-5 α -acetoxyafrican-2(6)-en-4-one (92) and 3 α ,4 α -dihydroxyafrican-2(6)-en-5-one (95). Previously, compound 106 was named norseswartzianin (40), but this was revised to norsescoswartzianin. The full structural establishment of all the africanes described above was discussed in detail by Tori and coworkers (848).

Bovi Mitre and associates reinvestigated the Argentinian *P. swartziana* and obtained the seven africanes 93–96 and 100–102, the three *seco*-africanes

103–105, and the two norsecoafricanes **106**, and **107**, among which **93**, **94**, **105**, and **107** were newly isolated compounds. Their absolute configurations were established mainly from CD measurements ([126](#)).

4.2.3 *Aristolanes*

Aristolene (**108**), 1(10)-aristolene (= calarene) (**109**), and 1(10),8-aristoladiene (**110**) were detected in the essential oil of *Calypogeia suecica* by GC/MS ([934](#)). The ether extracts of the New Zealand *Marsipidium epiphytum* and *Plagiochila circinalis* were analyzed by GC/MS to identify 1(10)-aristolene (**109**) and aristolone (**114**) ([635](#)). Compound **109** was detected also in the essential oil of *Saccogyna viticulosa* by GC and GC/MS ([276](#)). (–)-1(10)-Aristolene (**109**) was isolated from *Jungermannia infusca* as a minor constituent. In order to confirm its stereochemistry, **109** was degraded to aristolan-1-one (**109a**). Hydroboration of **109**, followed by oxidation with hydroperoxide gave aristola-1 β -ol (**109b**), which was oxidized with pyridinium chlorochromate (PCC)-aluminium oxide to yield ketone **109a**. The complete assignments of the ^1H and ^{13}C NMR chemical shifts of **109** were reported for the first time ([587](#)).



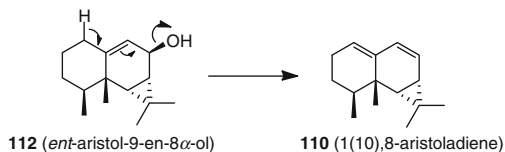
Aristolane- and *nor*-aristolane-type sesquiterpenoids found in the Marchantiophyta



Fig. 4.2 *Reboulia hemisphaerica*

Reboulia hemisphaerica (Fig. 4.2) is a rich source of various sesquiterpenoids. The ether extract of *R. hemisphaerica* showed a major constituent as a blue colored band on TLC and it was estimated to amount to at least 20% of the total extract. By chromatography on silica gel and Sephadex LH-20, and after preparative HPLC, the major compound was completely decomposed to give the known 1(10), 8-aristoladiene (**110**), which was isolated from a mushroom (916). Treatment of the crude extract on Sephadex LH-20 afforded the two methoxy products, **111** and **113**, indicating the previously unresolved major compound to be aristol-9-en-8-ol. Flash chromatography of the crude extract on silica gel furnished the major compound **112**, which immediately decomposed. Conclusive evidence for the structure of **112** was established as follows. Oxidation of **112** gave an α,β -unsaturated ketone for which the analytical data obtained were identical to those of aristolone (**114**), except for the sign of the optical rotation. Thus, it became clear that **112** is *ent*-aristol-9-en-8-ol. In order to confirm the absolute configuration of **112**, further experiments were performed. Catalytic asymmetric hydrogenation of **110** gave the diol **110a**, which was esterified with *p*-dimethylaminobenzoic acid, affording the benzoate **110b**, for which the CD spectrum showed a positive *Cotton* effect at 305 nm. The homoallyl benzoate rule suggested strongly that the absolute configuration of **112** is opposite to that of aristolone found in higher plants. The *axial* hydroxy group at C-8 was based on the facile dehydration of **112** (Scheme 4.1) (889).

Bazzania species are rich sources of sesquiterpenoids and bis(bibenzyls). The five new noraristolane sesquiterpenes, 4-*epi*-11-*nor*-aristola-1(10),11-diene (**115**), 4-*epi*-11-*nor*-aristola-1,9,11-triene (**116**), 4-*epi*-11-*nor*-aristola-9,11-diene (**117**) (–)-aristol-1(10)-en-12-ol (**118**), and (–)-aristol-1(10)-en-12-al (**119**) were isolated from the essential oil of the Japanese *B. japonica*, and their structures were elucidated



Scheme 4.1 Formation of (1(10),8-aristoladiene) from *ent*-aristol-9-en-8 α -ol

by a combination of 2D-NMR spectroscopy and by chemical correlations with compounds **116** and **117**, based on the same skeleton, by catalytic hydrogenation and analysis by capillary GC using a cyclodextrin-derived chiral adsorbent. A combination of 2D-NMR data analysis including NOESY and comparison of the fully hydrogenated products of **118** and **119**, and (+)- and (–)-aristolene by enantioselective GC on a modified cyclodextrin stationary phase, was used to establish the absolute configurations of **118** and **119**. These norsesquiterpenoids display no definite stereochemical relationship to the aristolanes present in *B. japonica* (485).

A methanol extract of the Patagonian *Adelanthus lindenbergianus* gave (–)- β -1,10-epoxyaristolane (**120**) (116), which was isolated from a marine organism, the sea pen *Scytalium splendens* (196).

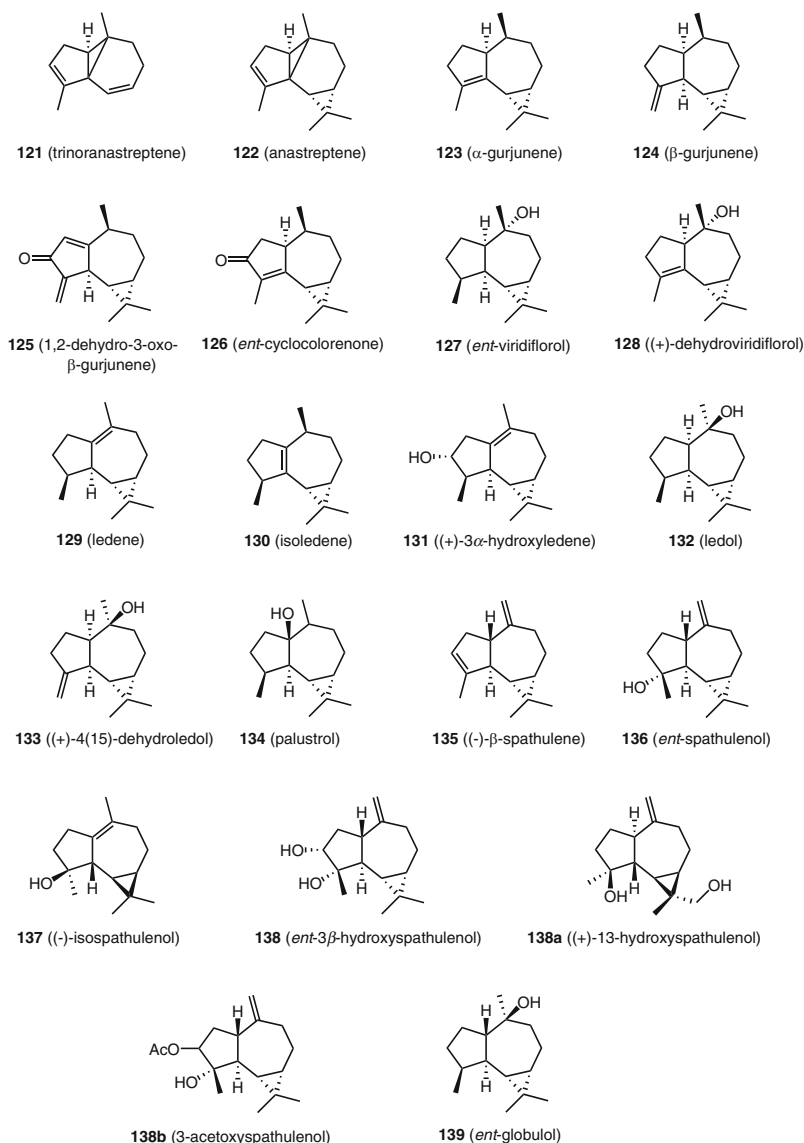
4.2.4 Aromadendranes and Zieranes

The trinoraromadendranes are very rare in Nature. *Bazzania praerupta*, *Barbilophozia floerkei*, and *Lophozia ventricosa* produce trinoranastreptene (**121**) (486, 15, 490).

Thermal rearrangement of bicyclogermacrene (**293**) at 300°C gave ledene (**129**) and bicycloelemene (**290**). Acid-catalyzed rearrangement of **293** in CHCl_3 yielded ledene (**129**) and aromadendrene (**156**) as major components and 9-*allo*-aromadendrene (**159**), γ -maaliene (**796**) and *allo*-aromadendrene (**158**), of which the latter compound was hydrogenated to furnish **159** and **129**. These results indicate that **293** is a biogenetic precursor of many other sesquiterpenoids in liverworts (933).

Aromadendrane sesquiterpenoids have been seen in a number of liverworts (39, 40), and almost all such sesquiterpenoids are enantiomeric to those found in higher plants.

Anastreptene (**122**), α -gurjunene (**123**), *ent*-cyclocolorenone (**126**), viridiflorol (**127**), and *ent*-spathulenol (**136**), which might originate from (–)-bicyclogermacrene (**293**) as well as *ent*-globulol (**139**), aromadendrene (**156**), and *allo*-aromadendrene (**158**), have been found in many different liverworts, especially in species of the Jungermanniales, as shown in Table 4.2.



Trinorsesquiterpene and aromadendrane-type sesquiterpenoids found in the Marchantiophyta

(+)-Spathulenol (**136**) and (+)-4 β ,10 α -dihydroxyaromadendrane (**171**) were isolated from two higher plants, *Phebalium tuberosum* ssp. *megaphyllum* and *P. filifolium*. (+)-Spathulenol (**136**) was also isolated from *Drummodita bassellii* and *D. calida*. (–)-Ledol (**132**) was found only in *Phebalium tuberosum* subsp. *megaphyllum*. *Eriostemon brucei* subsp. *brucei* produces (+)-13-hydroxyspathulenol (**138a**) (672), while 3-acetoxyspathulenol (**138b**) has been found in the soft coral *Parerythropodium fulvum* (938).

(–)-Ledol (**132**) has been purified from the ethyl acetate extract of the Chinese *Cephaloziella recurvifolia*, together with spathulenol. The same compound has also

been found in the Taiwanese *Bazzania tridens* together with cyclocolorenone (**126**) (951, 955).

(+)-*ent*-Cyclocolorenone (**126**) was obtained from an ether extract of an unidentified Venezuelan *Frullania* species (843), suspension cultured cells of *Porella vernicosa* (637), and *P. canariensis* (179, 582, 604) together with α -gurjunene (**123**). It is noteworthy that (+)-*ent*-cyclocolorenone (**126**) was isolated from the Indonesian soft coral *Nephthea chabrolii*, together with two related cyclopropane ring-opened derivatives (285), while (–)-cyclocolorenone was purified from *Solidago canadensis* and related species belonging to the Compositae, in large amounts (241).

ent-Viridiflorol (**127**) and myliol (**143**) have also been found in the French *Bazzania trilobata* (582) and *Anastrophyllum donnianum* (139). The former compound was isolated from the German *B. trilobata* (930) and *Lophozia ventricosa* (486).

The GC/MS analysis of 264 samples containing 87 species of liverworts showed the presence of (–)-bicyclogermacrene (**293**) in 41 species. Thus, **293** has been found as quite a common constituent in the liverworts, in addition to β -barbatene (**235**), 1-octen-3-yl acetate (**1941**), and *ent*-spathulenol (**136**). A pure sample of **293** was allowed to stand at room temperature and, after four days, was found to have changed completely to (–)-spathulenol. The conversion occurred quantitatively and the enantiomeric purity of **136** was equivalent to that of **293**. The crude ether extracts of seven fresh *Plagiochila* and three *Porella* species showed the presence of **293** and the absence of **235** by means of GC/MS. The GC/MS of these ether extracts performed seven to eight months after they were prepared, showed not only showed the absence of **293** but also the appearance of **136**. This indicates that **293** was completely transformed to **136**. This same transformation also occurs during the solvent extraction of liverworts.

Many species of liverworts and higher plants have been reported to contain spathulenol (**136**) and to date more than 500 papers have appeared concerning its detection and isolation from all plant species, particularly from their essential oils. In many cases, bicyclogermacrene (**293**) has been isolated or detected with spathulenol (**136**). The present results show that in many of these cases (if not all), (+)- or (–)-spathulenol (**136**) is artifactual and produced from (+)- or (–)-bicyclogermacrene (**293**) by autoxidation (870).

The ether extract of *Calypogeia azurea* was subjected to purification by column chromatography to yield the known 1,4-dimethylazulene (**230**) and the new 12-dehydro-3-oxo- β -gurjunene (**125**), for which the relative configuration was established by 2D-COSY NMR and X-ray crystallographic analysis (816). The essential oil obtained by hydrodistillation of *C. suecica* was analyzed by GC/MS to determine the presence of anastreptene (**122**), dehydroviridiflorol (**128**), and bicyclogermacrene (**293**) (934). The structure of **128** was identified as follows. This compound was hydrogenated to afford fully saturated diastereoisomeric aromadendranes, which were identical to the hydrogenated products of (–)-ledene (**129**) by enantioselective GC (933). The essential oil or dimethyl chloride extract of the German *Calypogeia muelleriana* was analyzed by GC/MS equipped with a column containing a chiral phase, and purified by preparative GC to give 4,5-dehydroviridiflorol (**128**) and 3 α -hydroxyledene (**131**). The latter alcohol was hydrogenated to give (–)-ledene (**129**), indicating that the new aromadendrene could be assigned as **131** (933).

(–)-*ent*-Viridiflorol (**127**), (–)-ledene (**129**), (+)-isolekene (**130**), (+)- α -gurjunene (**123**) (–)-aromadendran-5-ol (**169**), and (+)-aromadendr-4-en-12-ol (**170**) were isolated from the essential oil of *Conocephalum conicum*. When compound **169** was treated with phosphoryl chloride, compounds **123**, **130**, and γ -gurjunene (**732**) were obtained. The same treatment of (+)-**170** resulted in the formation of (+)-dehydroviridiflorol (**128**). Enantioselective GC showed the absolute configurations of both compounds **169** and **170** to be the same (**544**).

ent-4 β ,10 α -Dihydroxyaromadendrane (**171**), which was found in two *Plagiochila* species (**477**, **579**), was isolated from *Lepidozia fauriana* (**747**). The same compound and (–)-*ent*-ledene (**129**) have been isolated from *Jackiella javanica* belonging to the Lophoziaaceae (**614**). The latter compound was obtained from the Madagascan *Bazzania madagassa* (**293**). 5 β -Hydroxy-*ent*-aromadendr-1-en-3-one (**174**) was obtained from *Lepidozia spinosissima* along with *ent*-spathulenol (**136**) (**72**, **611**, **616**).

The Colombian *Lepicolea pruinosa* (**263**) has been studied chemically and two sesquiterpene lactones, frullanolide (**658**) and its dihydro derivative, **660**, have been detected. The GC/MS analysis of an ether extract of the Chilean *L. ochroleuca* indicated that the known ledol (**132**) was almost the sole major component. Further purification of the crude extract by means of HPLC afforded three aromadendranes, *ent*-3 β -hydroxySPATHULENOL (**138**), 1,10-dioxotayloriane (**148**), and *ent*-4 β -hydroxy-10 α -methoxyaromadendrane (**172**), along with ledol (**132**) and palustrol (**134**) (**478**). All of the structures were elucidated by a combination of 2D-NMR methods and comparison of the spectroscopic data obtained with those of known *seco*-aromadendranes. 2,10-*seco*-Aromadendranes have been found in the liverwort *Mylia taylorii* (**40**). However, compound **148** was not found in this liverwort, but is known as a synthetic compound (**115**).

The essential oils of the Taiwanese *Lepidozia fauriana* were analyzed by GC/MS to detect viridiflorol (**127**), (–)-isospathulenol (**137**), globulol (**139**), isolekene (**130**), aromadendrene (**156**), and *allo*-aromadendrene (**158**) (**645**), compounds occurring as well in the higher plant, *Salvia scarea* (**531**).

The Austrian *Mylia taylorii* also elaborates many kinds of aromadendranes and *seco*-aromadendranes. Nagashima and Asakawa isolated (+)-4(15)-dehydroledol (**133**), (+)-globulol (**139**), (+)-4(15)-dehydroglobulol (**140**), (–)-myliol (**143**), (–)-taylorione (**145**), and myltayloriones A (**149**) and B (**150**), together with (+)-*ent*-maali-4(15)-en-1 β -ol (**803**) (**569**). *ent*-Globulol (**139**) has been isolated from the Madagascan *Bazzania madagassa* (**293**), *Lophozia ventricosa* (**486**) and the Japanese *Jackiella javanica* (**608**).

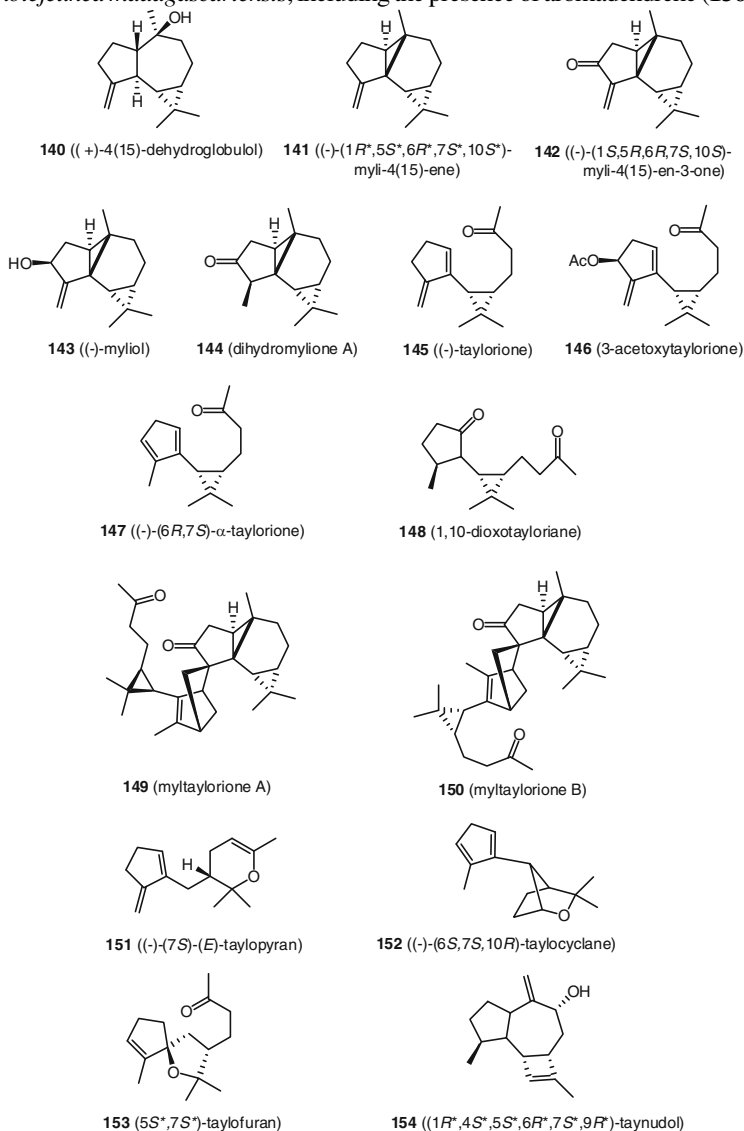
Assignments of the ^{13}C NMR spectroscopic data of the commercially available (–)-globulol were revised by means of the 2D-NMR (^1H - ^1H COSY, HMBC and NOESY) data obtained for (+)-globulol (**139**), isolated from the liverworts, *Plagiochila ovalifolia*, *Neotrichocolea bissetii*, and *Pallavicinia subciliata* (**891**).

Tridensenone (**155**) has been isolated previously from *Bazzania tridens* (**40**) and found also from *Bazzania japonica* (**485**). The same compound (**155**) occurs in the Australian marine soft coral *Parerythropodium fulvum*. However, the absolute configuration remains to be clarified (**938**).

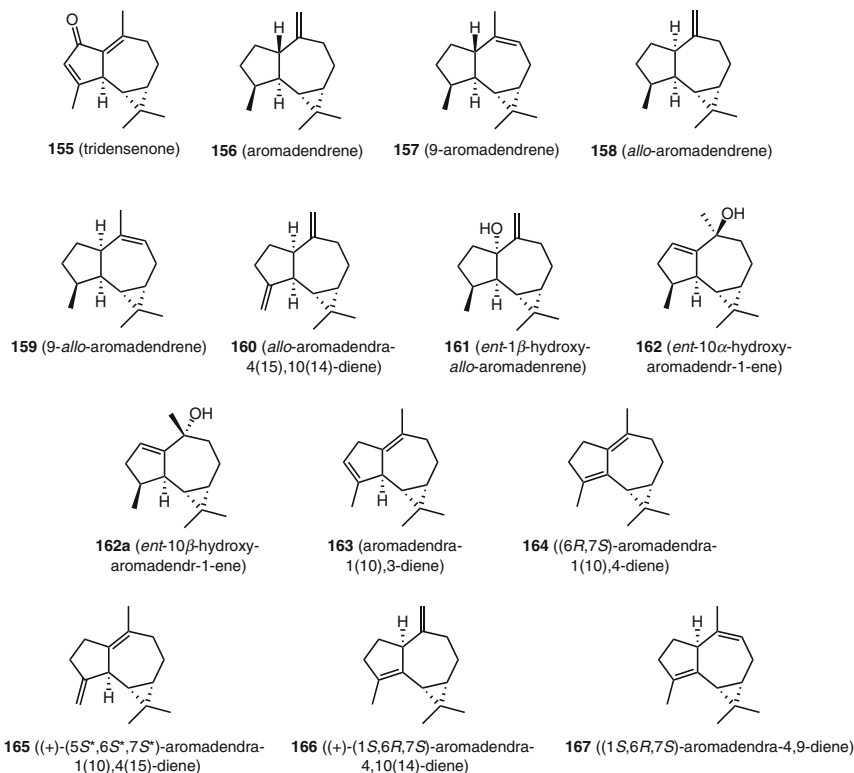
The reinvestigation of the essential oils of *Saccogyna viticulosa* resulted in the identification of two new aromadendranes, (–)-*allo*-aromadendra-4(15),10(14)-diene (**160**) and aromadendra-4(15),10(14)-dien-1-ol (**168**), together with anastreptene (**122**).

The stereostructures of both new compounds identified by 2D-NMR spectroscopy were confirmed by chemical correlation between **168** and (–)-*allo*-aromadendrene (**158**). Catalytic hydrogenation of both compounds gave tetrahydro and dihydro products. GC analysis using a heptakis(2,6-di-*O*-methyl-3-*O*-pentyl)- β -cyclodextrin column showed that **160** possesses the (1*R*,5*S*,6*S*,7*S*) configuration. The structure of **168** was proposed from 2D-NMR experiments. The position and configuration of a tertiary hydroxy group at C-1 were determined by the observation of diagnostic NOEs (276).

Application of the HS-SPME (head space-solid phase micro-extraction) technique coupled with GC/MS analysis led to the detection of volatile components of *Drepanolejeunea madagascariensis*, including the presence of aromadendrene (**156**) (247).



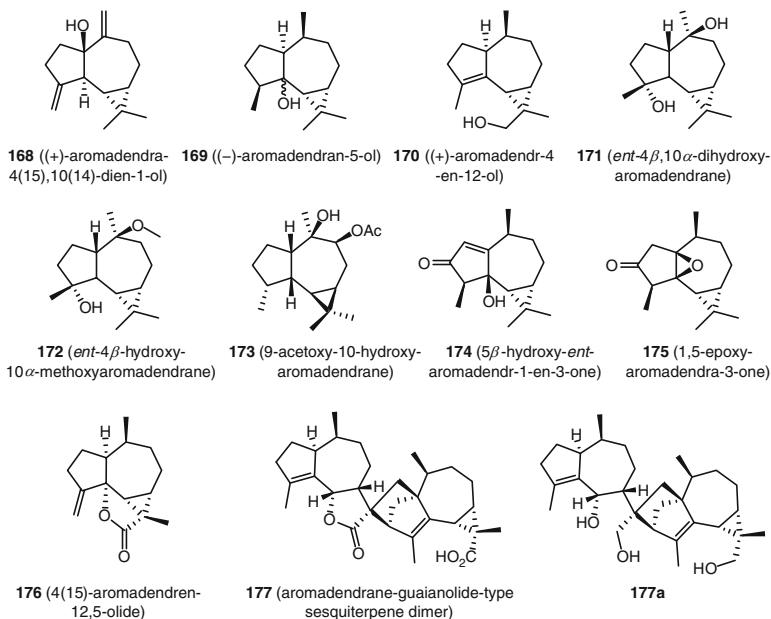
Aromadendrane- and 1,10-*seco*-aromadendrane-type and their related sesquiterpenoids found in the Marchantiophyta



Aromadendrane-type sesquiterpenoids found in the Marchantiophyta

The two aromadendranes **161** and **162** were isolated from the ether extract of the New Zealand *Lepidozia setigera* (347). The former was identical to *ent*-1 β -hydroxy-*allo*-aromadendrene (**161**) isolated from the red alga *Laurencia subopposita* (946). Its enantiomer was obtained as the biotransformation product of *allo*-aromadendrene (**158**) (5). Compound **162** was deduced as *ent*-10 α -hydroxyaromadendr-1-ene by 2D-NMR methods, including the NOESY spectrum. The C-10 stereoisomer, *ent*-10 β -hydroxyaromadendr-1-ene (**162a**), was isolated from the red alga *L. subopposita* (946).

The essential oil of *Plagiochila asplenioides* was purified by preparative GC to obtain (–)-aromadendra-1(10),3-diene (**163**), for which the stereostructure was proposed based on 2D-NMR experiments (COSY, HMBC, HMQC, NOESY) (14).



Aromadendrane-type sesquiterpenoids and aromadendrane-dimers found in the Marchantiophyta

Mylia species are a rich source of aromadendrane and 1,10-*seco*-aromadendrane sesquiterpenoids (40). Further GC/MS analysis of essential oil samples of *M. taylorii* collected in Austria, Germany, and Canada, and that of the Taiwanese *M. nuda* showed the presence of a number of previously known aromadendrane, myltaylane, and cyclomyltaylane sesquiterpenoids. Additional fractionation of the essential oil samples of *M. taylorii* resulted in the isolation of 13 new sesquiterpenoids, with five being of the aromadendrane type, namely, myli-4(15)-ene (141), aromadendra-1(10),4(15)-diene (165), aromadendra-4,10(14)-diene (166), aromadendra-4,9-diene (167), and myli-4(15)-en-3-one (142), together with anastreptene (122), myliol (143), dihydromylione (144), 4(15)-dehydroglobulol (140), *ent*-globulol (139), dehydroviridiflorol (128), and aromadendra-1(10),4-diene (164). All of the relative stereostructures were determined by 2D-NMR procedures. The absolute configuration of 142 was confirmed by chemical correlation with 143 and 144, of known absolute configuration. Compound 142 has been proposed as a natural precursor for the dimeric myltayloriones 149 and 150 (922).

The absolute configurations of 166 and 167 were established by dehydration of 4-dehydroviridiflorol (128), a compound of known absolute configuration. Treatment of 128 with (+)-methanesulfonyl chloride gave 166, 167, and (–)-(6*R*,7*S*)-aromadendra-1(10),4-diene (164). All of the compounds mentioned above and 4(15)-dehydroglobulol (140), *ent*-globulol (139), and dehydroviridiflorol (128) have been detected in the Taiwanese *Mylia nuda* by NMR and GC/MS. Compounds 164, 166, and 167 have been found in the liverworts *Barbilophozia*, *Diplophyllum albicans*, and *D. plicatum* species (15). The essential oil of the Austrian *Kurzia trichoclados* contained the aromadendranes anastreptene (122), globulol (139), myliol (143), dihydromylione A (144), *allo*-aromadendrene (158), aromadendra-1(10)-4-diene

(**164**), aromadendra-1(10),4(15)-diene (**165**), aromadendra-4,9-diene (**167**), and the 1,10-*seco*-aromadendranes, taylorione (**145**) and taylopyran (**151**) (**922**).

The essential oil of *Mylia taylorii* and *M. nuda* elaborates not only aromadendranes but also the new 1,10-*seco*-aromadendranes, (6*R*,7*S*)- α -taylorione (**147**) and 6,11-*seco*-taylori-3,5,9-trien-10,11-oxide (= (7*S*)-(*E*)-taylopyran) (**151**), 6,11-*seco*-6,10-cyclotayloridiene-10,11-oxide (= taylocyclane) (**152**), and 6,11-*seco*-taylori-3-en-10-on-5,11-oxide (= taylofuran) (**153**), together with the known taylorione (**145**) and 3-acetoxytaylorione (**146**). The absolute configuration determination of **147** was based on the chemical correlation with **145**, having a known absolute configuration (**40**). Treatment of **145** with the acidic ion-exchange resin Amberlyst[®] afforded **147**, **152**, and **153**, which might be cyclized from **151**. The absolute configuration of **151** was settled by the co-identity of the natural product with (–)-(7*S*)-(*E*)-taylopyran obtained by rearrangement of (–)-(6*R*,7*S*)-taylorione (**145**). The absolute configurations of the remaining compounds, **152** and **153**, were suggested by the presence of the co-occurring tayloriane sesquiterpenoids in *M. taylorii*. Compounds **147**, **151**, **152**, and **153** were also detected in the *n*-hexane, methylene chloride, ether, and methanol extracts of crushed and intact *M. taylorii* and *M. nuda* plant materials by GC/MS, although they were considered to be artifacts. Taylorione (**145**) was detected in the essential oil of *M. nuda* by GC/MS (**922**).

Myliol (**143**) and its derivatives as well as 1,10-*seco*-aromadendranes are believed to be specific chemical markers of the Myliioidae. However, myliol (**143**), taylorione (**145**), and taylopyran (**151**) were also detected in the essential oil of the Austrian liverwort *Kurzia trichoclados*, which belongs to the Lepidoziaceae and is morphologically different from the Myliioidae (**922**).

The 2,5,8-trimethyl-decahydro-cyclobutan[*e*]azulene sesquiterpenoid (taynudol) (**154**), was isolated from the essential oil from *Mylia taylorii* and detected in the Taiwanese *M. nuda*, and its relative stereostructure was based mainly based on the analysis of its 2D-NMR spectra. It was suggested that the new carbon skeleton of **154** might originate from a guai-11-ethyl-6-carbenium ion (**922**).

The Taiwanese *Plagiochila pulcherrimum* was fractionated further to give the previously known *ent*-4 β ,10 α -dihydroxyaromadendrane (**171**) (**477**), which was isolated from the Japanese *P. ovalifolia* (**40**). *Tylimanthus renifolius* produces 9-acetoxy-10-hydroxyaromadendrane (**173**) with a 1 β ,4 α ,5 β ,6 α ,7 α ,9 β ,10 β - configuration. Its structure was based on the comparison of NMR data with those of the known 10-aromadendranols viridiflorol (**127**) and globulol (**139**) (**213**).

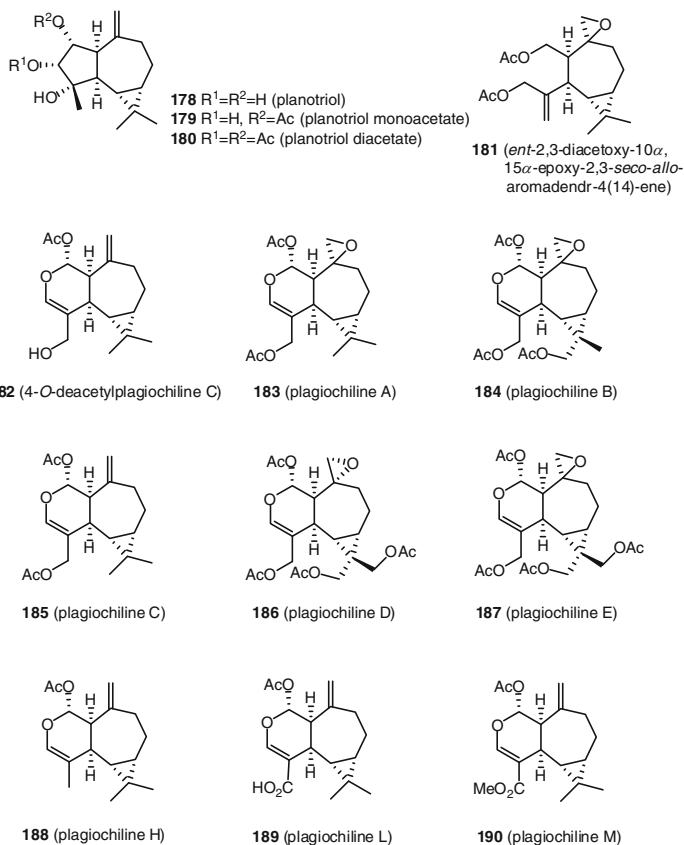
Heteroscyphus planus produces 2,3-*seco*-aromadendranes (**310**) and cadinane sesquiterpenoids (**560**, **561**). Further fractionation of the ether extract of *Heteroscyphus coalitus* on silica gel and Sephadex LH-20 resulted in the isolation a new 5-hydroxyaromadendrone (**174**), the structure of which was established as 5 β -hydroxy-*ent*-aromadendr-1-en-3-one. This determination was by analysis of the 2D-NMR data of the isolated compound and of its allylic alcohol obtained by reduction with lithium aluminum hydride, in addition to the X-ray crystallographic analysis of **174** (**873**). *Lepidozia spinosissima* contained the same compound (**174**) and *ent*-spathulenol (**136**) (**616**). Compound **174** has been isolated previously from *Heteroscyphus coalitus* (**873**).

The ether extract of *H. coalitus* was fractionated to give a new aromadendranone for which the structure was determined to be 1,5-epoxyaromadendra-3-one (**175**) by 2D-NMR (COSY, HMBC, NOESY) data analysis. The β -configuration of an epoxy ring present in the molecule was confirmed by the diagnostic shifts of H-2, H-4, and H-6 in the NMR spectrum of compound **175** when measured in $\text{Eu}(\text{fod})_3$ in CCl_4 . This was confirmed by the formation of 1 β -hydroxycyclocolorone by the treatment of **175** with HClO_4 in $\text{THF}/\text{H}_2\text{O}$ (617).

The ether extract of the New Zealand *Chiloscyphus subporosus* contained a new aromadendrane lactone (**176**) and an aromadendrane-guaiane dimer (**177**), along with spathulenol (**136**). The structure of **176** was deduced by 2D-NMR methods, including HMBC and phase-sensitive NOE exchange spectroscopy (Ph-NOESY). However, the Ph-NOESY spectrum did not provide clear information on the overall stereochemistry. The final relative stereostructure was established as 4(15)-aromadendren-12,5 α -olide for **176** by X-ray crystallographic analysis. The structural determination of the dimer **177** was based on 2D-NMR data and Cotton effects. The conclusive structure of **177** was established by X-ray crystallographic analysis of the triol **177a** obtained by the reduction of **177** with LiAlH_4 . The presence of this aromadendrane-guaiane dimeric sesquiterpene is the first such record among the liverworts, although eudesmane-eudesmane, aromadendrane-eudesmane, and eudesmane-fusicoccane (diterpene) dimers have been isolated from a small number of liverworts (40). *Chiloscyphus* species in addition elaborate chiloscyphane and oppositane sesquiterpenoids. The present species, however, was not found to contain such compounds (606).

The methanol extract of the cultured cells of *Heteroscyphus planus* was purified by HPLC to give *ent*-trihydroxy-*allo*-aromadendrane (= planotriol) (**178**) and its acetates, planotriol monoacetate (**179**) and planotriol diacetate (**180**), which were hydrolyzed with Cs_2CO_3 to give the parent compound. The relative configuration of **178** was proven by extensive 2D-NMR data analysis (^1H - ^1H , ^1H - ^{13}C COSY, HMBC, NOE, NOESY). Planotriol (**178**) was esterified by benzoyl chloride to give a dibenzoate for which X-ray crystallographic analysis was used to establish the stereostructure of **178**. The absolute configuration of the monoacetate **179** was established by the presence or absence of NOE enhancement of the acetoxy methyl protons by the irradiation of the methoxy protons in the axially chiral MNCB ester (*aS*) and (*aR*) of the secondary hydroxy group at C-3 (234). The (*R*)-configuration at C-3 was also proven by chemical shift differences defined as $\Delta\delta = \delta(\text{aS}) - \delta(\text{aR})$ (ppm) of the MNCB esters (562).

The methanol extract of the cultured cells of *H. planus* was purified by HPLC to afford two new *ent*-2,3-*seco*-aromadendrane, *ent*-2,3-diacetoxy-10 α ,15 α -epoxy-2,3-*seco*-*allo*-aromadendr-4(14)-ene (**181**) and *ent*-deacetylplagiochiline C (**182**), together with plagiochiline A (**183**) and methoxyplagiochiline A₂ (**210**). Compound **182** was reported as a reduced product of plagiochiline L (**189**) (310). Acetylation of **182** gave a diacetate, which was identical with plagiochiline C (**185**). The structure of **181** was deduced by 2D-NMR data and comparison of the NMR data with those of plagiochiline A (**183**) (562).

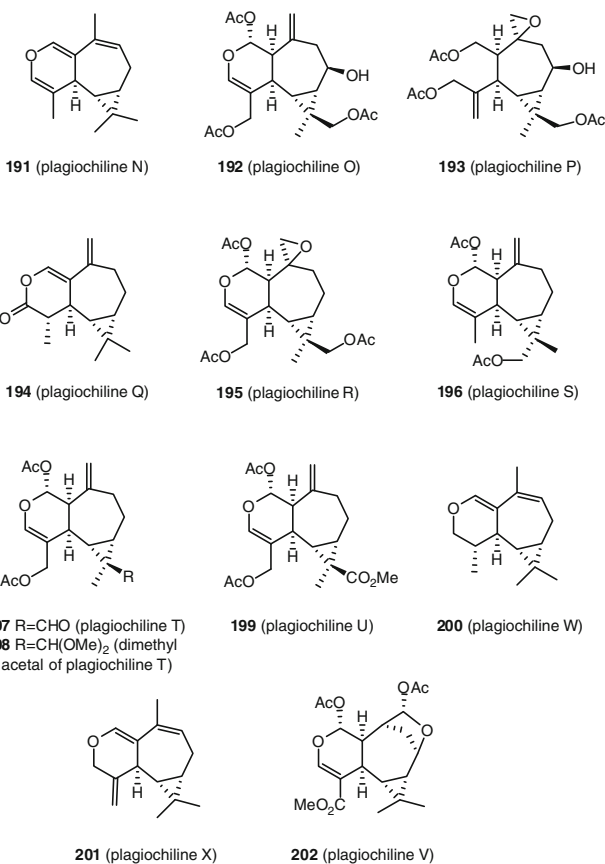


Aromadendrane- and 2,3-*seco*-aromadendrane-type sesquiterpenoids found in the Marchantiophyta

Plagiochila species are rich sources of highly oxygenated *ent*-2,3-*seco*-aromadendrane sesquiterpenoids of which some have a potent hot-tasting effect. These compounds are significant chemosystematic markers of the Plagiochilaceae (see Sect. 8.). Scottish and English samples of *Plagiochila atlantica* and *P. aerea* were extracted with deuteriochloroform. The ^1H NMR spectrum of each crude extract indicated the presence of plagiochiline C (**185**). The latter species also produced plagiochiline A (**183**) (334, 691). The Taiwanese *Plagiochila pulcherrimum* was further fractionated to give compounds in the previously known same 2,3-*seco*-aromadendrane series, namely, plagiochilines A (**183**), B (**184**), and C (**185**) (477). The ether extract of the New Zealand *Plagiochila invurvicolla* was fractionated by CC to give plagiochilines C (**185**) and E (**187**) (558).

The ether extract of *Heteroscyphus planus* was fractionated using CC to give two new *ent*-2,3-*seco*-aromadendranes, plagiochilines L (**189**) and M (**190**), together with plagiochiline C (**185**). The complete structures **189** and **190** were based on the comparison of their spectroscopic data with those of plagiochiline C (**185**) and by chemical transformation. Treatment of **189** with oxalyl chloride and $NaBH_4$, followed by acetylation, provided plagiochiline C (**185**). Methylation of **189** with diazomethane gave a methyl ester identical to plagiochiline M (**190**). This was the first report of the isolation of 2,3-*seco*-aromadendranes from the Lophocoleaceae (310).

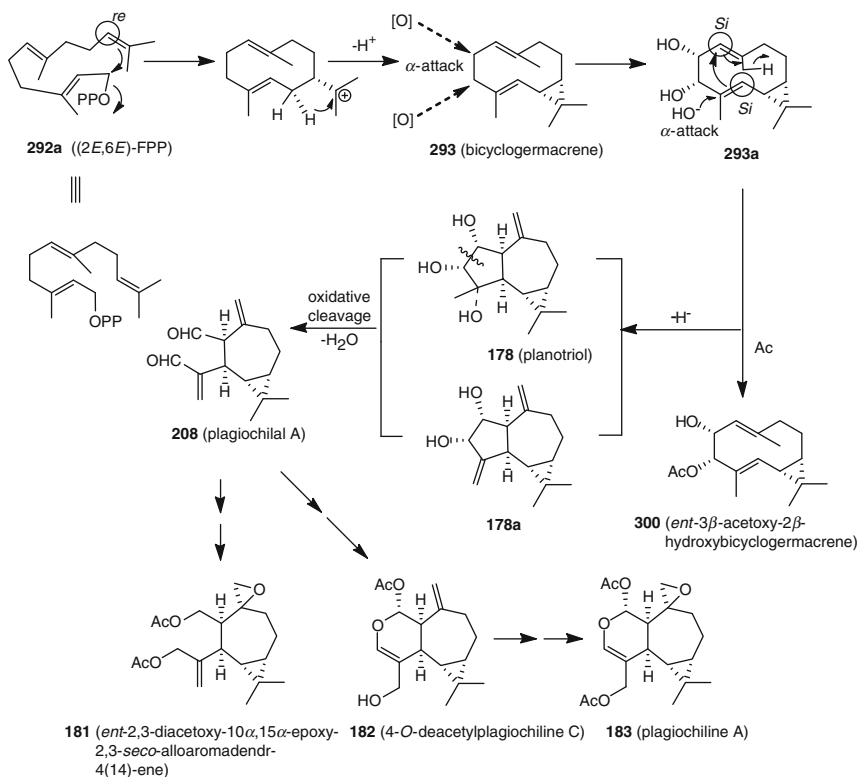
Blay and coworkers synthesized the 2,3-*seco*-aromadendrane, plagiochiline N (**191**), which was isolated from *Plagiochila ovalifolia* (**40**) through *O*-acetyliso-photosantonin prepared from α -santonin in a 15-step reaction sequence (**117**).



2,3-*seco*-Aromadendrane-type sesquiterpenoids found in the Marchantiophyta

Asakawa proposed a biosynthesis pathway for 2,3-*seco*-aromadendranes via plagiochilal A (= hanegokedial) (**208**) from bicyclogermacrene (**293**) (**39**, **40**). Nabeta and associates also proposed the biosynthesis hypothesis that 2,3,4-trihydroxy-*allo*-aromadendrane (**178**) or *ent*-2,3-dihydroxy-*allo*-aromadendrane (**178a**) is an intermediate in the formation of the 2,3-*seco*-aromadendrane derivatives, such as (–)-hanegokedial (**208**), *ent*-2,3-diacetoxy-10 α ,15 α -epoxy-2,3-*seco*-*allo*aromadendra-4 (14)-ene (**181**), *ent*-deacetylplagiochiline C (**182**), and plagiochiline A (**183**), and other compounds in the plagiochiline series (Scheme 4.2) (**562**).

Further investigation of lipophilic compounds of *Plagiochila asplenioides* afforded plagiochiline P (**193**) (**441**). The ethyl acetate fraction of the Taiwanese *Plagiochila elegans* was chromatographed over silica gel to give the new 2,3-*seco*-aromadendrane sesquiterpenoid, *iso*-plagiochilide (**204**), the double bond isomer of plagiochilide (**203**), together with plagiochiline C (**185**). The structure of **204** was deduced from its 2D-NMR spectra including HMBC. The presence of plagiochiline H (**188**) was identified by GC/MS of the crude extract of *P. elegans* (**470**). A methanol extract of



Scheme 4.2 Possible biogenesis pathways for 2,3-seco-aromadendrane-type sesquiterpenoids

the cell suspension culture of *Plagiochila ovalifolia* was analyzed by GC/MS to identify ovalifoliene (**205**) (529). The ether extract of the European *Plagiochila asplenioides* was further investigated to afford plagiochiline C (**185**), ovalifolienal (**206**), plagiochilal A (**208**), and hanegoketrial (**209**) (40, 604).

The ether extract of the European *Porella porelloides* also contained fatty acid esters of 2,3-seco-aromadendrane-15-ol (mixture A (**213** and **214**) and plagiochiline A-15-yl (4Z)-decenoate (**215**)), together with plagiochiline D (**186**) and *ent*-spathulenol (**136**). The structure of mixture A was confirmed by comparison of the spectroscopic data with those of plagiochilines A (**183**) and B (**184**). NOE difference experiments indicated that in mixture A the fatty acyl group was at C-15, because a NOE was observed between H-14 and H-5, and H-15. Reduction of this mixture with LiAlH_4 gave *n*-octanol and *n*-decanol by GC/MS analysis, and the proportion was almost 1:2 in the total ion chromatogram. On the basis of the above data, mixture A was composed of plagiochiline A-15-yl octanoate (**213**) and plagiochiline A-15-yl decanoate (**214**). The structure of **215** was deduced to be plagiochiline A-15-yl (4Z)-decenoate by comparison with the spectroscopic data of **213** and **214**. The presence of the 4'-*cis* proton on the double bond of the fatty acid moiety was proven by spin-spin decoupling experiments. Compound **215** was treated with LiAlH_4 , followed by hydrogenation, to afford an alcohol for which the physical and spectroscopic data were identical with those of *n*-decanol by GC/MS (867). The ether extract of the Japanese liverwort, *Plagiochila*



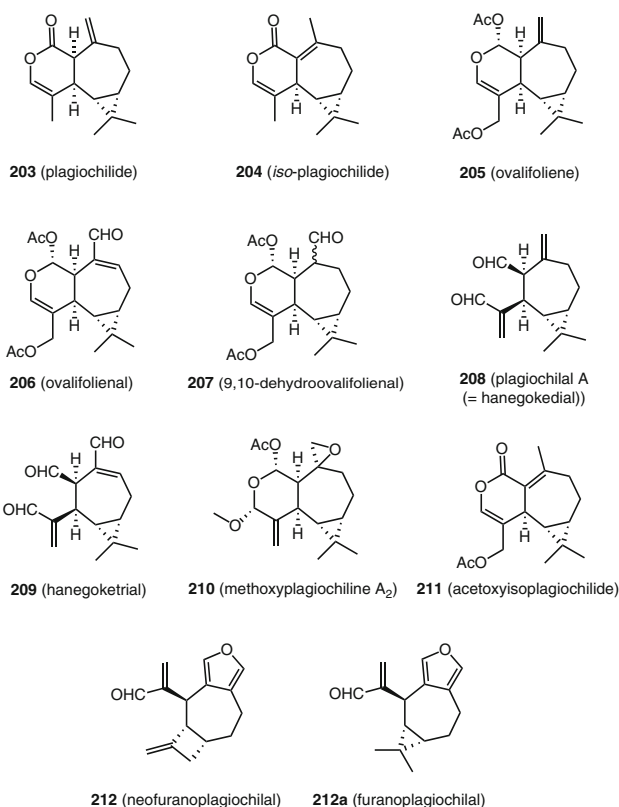
Fig. 4.3 *Plagiochila ovalifolia*

ovalifolia (Fig. 4.3) gave three new 2,3-*seco*-aromadendranes, plagiochiline A-15-yl hexanoate (**216**), 14-hydroxyplagiochiline-A 15-yl (2*E*,4*E*,8*Z*)-tetradecatrienoate (**217**), and 14-hydroxyplagiochiline-A 15-yl (2*E*,4*E*)-dodecadienoate (**218**), together with **213** and **215**. The structures of **216–218** were characterized by comparison of the spectroscopic data with those of the known plagiochiline A (**183**) and plagiochiline-A 15-yl octanoate (**213**) as well as by 2D-NMR (COSY, HMQC, HMBC, NOESY) data interpretation. The assignment of the proton signals at C-14 and C-15 was inferred from 2D-NMR NOESY information. The configurations of the double bond at C-2', C-4' and C-8' in **217**, and C-2 and C-4' in **218** were confirmed as (*E*) for the former two double bonds and (*Z*) for C-8' for **217** and (*E*) for **218**, on the basis of the ^1H NMR coupling constants (888). Further chemical analysis of the same *P. ovalifolia* specimen gave additional plagiochiline esters (**219–223**) (44, 881).

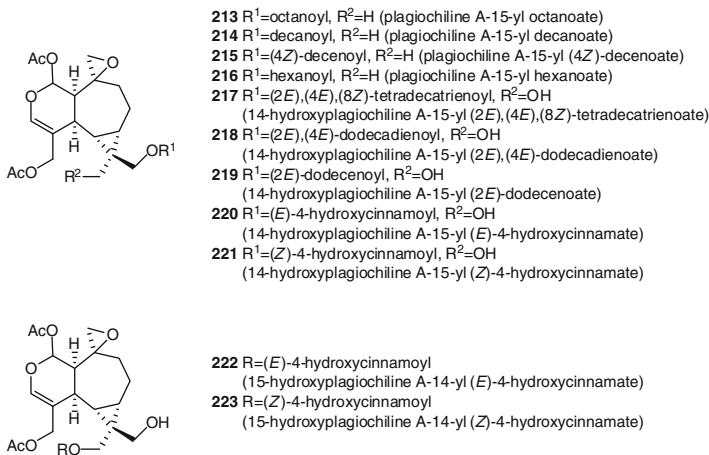
Purification of the ether extract of the Colombian *Plagiochila cristata* and the African alpine *P. ericicola* by CC and HPLC led to the isolation of three new *ent*-2,3-*seco*-aromadendranes, plagiochilines O (**192**), P (**193**), and Q (**194**), from the former species, and the new plagiochiline R (**195**), from the latter, together with known plagiochilines C (**185**) and H (**188**) and (–)-spathulenol (**136**) from both species. The dichloromethane extract of axenic *P. adianthoides* was also treated in the same manner as *P. cristata* to give two new 2,3-*seco*-aromadendranes, plagiochiline S (**196**) and 9,10-dihydroovalifolienal (**207**), together with plagiochilines A (**183**) and H (**188**). The ether extract of the Rwandan *P. squamulosa* var. *sinuosa* contained the known *iso*-plagiochilide (**204**) (911), which was isolated from *P. elegans* (470). The structures of **192–194** and **195** were assigned by 2D-NMR analysis and comparison with the ^1H and ^{13}C NMR spectra of plagiochiline C (**185**) and plagiochiline B (**184**), the C-11-isomer of **195**. The NMR spectra of **196** were very similar to those of plagiochiline C (**185**) and H (**188**), indicating the presence of the plagiochiline skeleton with an exomethylene group. The presence of two acetoxy groups was based on analysis of the NMR spectra. The structure of **207** was assigned by 2D-NMR analysis and comparison with the analogous data of ovalifolienal (**206**), which was isolated from *P. ovalifolia* (40).

The Scottish *Plagiochila carringtonii* was extracted with deuterated chloroform to give two new compounds, plagiochilines T (**197**) and U (**199**). The methanol extract also contained plagiochiline T (**197**) and its dimethyl acetal **198** in about a 2:1 ratio. The relative configuration of **197** was suggested by comparison of its NMR spectroscopic data with those of plagiochiline C (**185**). The position of the aldehyde group present was proven using the NOE experiment. Compound **199** was also assigned as plagiochiline C (**185**), having a methoxycarbonyl group at C-13, by comparison with the NMR data of plagiochiline T (**197**) (**697**).

The chemical constituents of *Plagiochila asplenioides* have been reported, and 2,3-*seco*-aromadendranes, such as plagiochiline A (**183**), were isolated (**40**). Further fractionation of the essential oil of *P. asplenioides* gave two new *seco*-aromadendranes, named plagiochilines W (**200**) and X (**201**), together with plagiochiline H (**188**). The structures of **200** and **201** were assigned by comparison of the spectroscopic data of those of plagiochiline H (**188**) along with 2D-NMR (COSY, HMBC, HMQC) data analysis, and from the co-occurrence of (–)-bicyclogermacrene (**293**) and (–)-**163** (**14**). From *Plagiochila porelloides* collected in China, plagiochiline C (**185**) and the new plagiochiline V (**202**) were detected. The structure of **202** was proposed for plagiochiline V by NMR coupling constant analysis and the constraints imposed by the ether linkage from C-8 to C-14 (**762**).



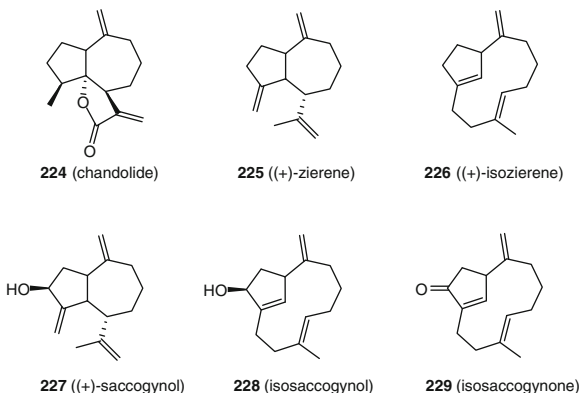
Bioactivity-guided fractionation of the ether extract of an unidentified Tahitian *Plagiochila* species using the DPPH radical-scavenging assay resulted in the isolation of the new 2,3-*seco*-aromadendrane, neofuranoplagiochilal (**212**), for which the structure and relative configuration were assigned by the 2D-NMR data obtained, inclusive of the NOESY spectrum (701). Compound **212** might be formed from furanoplagiochilal (**212a**) isolated from Japanese *Plagiochila* species such as *P. hattoriana* and *P. yokogurensis* (39).



2,3-*seco*-Aromadendrane-type sesquiterpenoids found in the Marchantiophyta

The ether extracts of *Porella ovalifolia* and *P. yokogurensis* were reinvestigated chemically to isolate plagiochiline A-15-yl hexanoate (**216**) from the former species, and a new dimeric 2,3-*seco*-aromadendrane/fusicoccane dimer (**1123**), together with plagiochilide (**203**), and plagiochiline C (**185**) from the latter (84). *Diels-Alder* reaction-type dimers between eudesmane and fusicoccane have been found in *Plagiochila moritziana* (40).

The zierane carbon skeleton is very rare in Nature. The ether extract of the Tahitian *Chandonanthus hirtellus* (Fig. 4.4) was purified by CC to give a new 7,11-*seco*-aromadendrane sesquiterpene lactone, named chandolide (**224**), for which the stereochemistry was established as a result of its X-ray crystallographic analysis (423).



Zierane-type sesquiterpenoids found in the Marchantiophyta

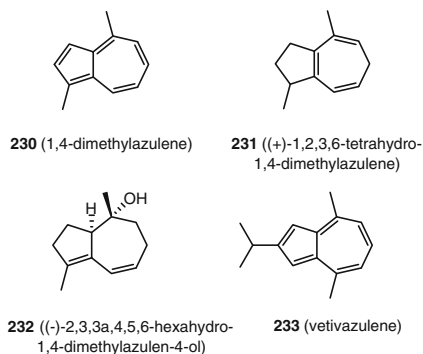


Fig. 4.4 *Chandonanthus hirtellus*

Previously, *Connolly* and associates reported the isolation of two zierane sesquiterpenoids, deoxysaccogynol (= zierene) (**225**) and saccogynol (**227**) from the Scottish *Saccogyna viticulosa*. A full paper concerning these two structures was published by the same authors ([164](#)). A reinvestigation of the essential oil of *Saccogyna viticulosa* by GC and GC/MS resulted in the identification of zierene (**225**) (29%) and its *Cope* rearranged product, isozierene (**226**), along with saccogynol (**227**) (17%), isosaccogynol (**228**), and isosaccogyone (**229**). Indeed, when **225** was injected into a GC instrument at varying injection port temperatures, isozierene (**226**) was detected ([276](#)).

4.2.5 Azulenes

The distribution of azulenoids in liverworts is restricted to a few *Calypogeia* and *Plagiochila* species ([40](#)). The ether extract of *Calypogeia azurea* was chromatographed by CC to yield the known 1,4-dimethylazulene (**230**) ([816](#)).



Azulene-type sesquiterpenoids found in the Marchantiophyta

Barbilophozia floerkei produces dolabellane and fusicoccane diterpenoids (40). Reinvestigation of the chemical constituents of the essential oil of this liverwort resulted in the isolation of two new trinorsesquiterpenes, (+)-1,2,3,6-tetrahydro-1,4-dimethylazulene (231) and (–)-2,3,3a,4,5,6-hexahydro-1,4-dimethylazulen-4-ol (232), along with the known trinoranastreptene (121) and 1,4-dimethylazulene (230), and the identification of a number of more common sesquiterpene hydrocarbons, e.g. anastreptene (122), *allo*-aromadendra-4(15), 10(14)-diene (160), *trans*- β -bergamotene (273), 3 α -acetoxybicyclogermacrene (298), β -bisabolene (315), and tritomarene (915). The stereostructures of 231 and 232 were deduced by 2D-NMR (COSY, HMBC, HMQC, NOESY) spectroscopic analysis. Treatment of trinoranastreptene (121) with Amberlyst® 15 resin gave the natural products 231 and 232. Compounds 231 and 232 could be either naturally occurring or else artifacts caused by the isolation processes (15).

4.2.6 Barbatanes

Barbatanes (= gymnomitranes) were once believed to be unique to the liverworts and not found in higher plants. However, König and associates isolated (–)- α -barbatene (234), (+)- β -barbatene (235), and (–)-isobarbatene (235a) from the essential oil of the roots of the higher plant *Meum athamanticum* (434). It is noteworthy that the absolute configurations of the isolated compounds 234 and 235 were confirmed as enantiomers of those found in the liverworts by capillary column chromatography on (6-*O*-methyl-2,3-di-*O*-pentyl)- γ -cyclodextrin (434). (–)- α -Barbatenal (= α -barbatene-15-al) (256) was also isolated from the higher plant, *Joannesia princeps* (7).

(–)- β -Barbatene (235) is a common compound among the liverworts. It has been found mainly in the stem-leafy liverworts, inclusive of the Taiwanese *Plagiochila elegans* (470), *Barbilophozia floerkei* (583), *Plagiochila sciophila* (492), the New Zealand *Plagiochila circinalis*, *Marsupidium epiphytum*, an unidentified *Heteroscyphus* species, *Jamesoniella colorata*, *Bazzania novae-zealandiae* and *B. tayloriana* (72, 635), the Ecuadorian *Anastrophyllum auritum* (976), the Finnish *Barbilophozia barbata* and *B. hatcheri* (596), and the German *Plagiochila asplenioides* (604). Compound 235 occurs also in the thalloid liverworts *Reboulia hemisphaerica* (929) and *Dumortiera hirsuta* (96), among others (Table 4.2).

Labeling experiments with 1-¹³C, 2-¹³C-, and 6,6-D₂-glucose and 4,4-D₂ mevalolactone (MVL) to investigate gymnomitrane biosynthesis in tissue cultures of *Reboulia hemisphaerica* and *Bazzania trilobata* were carried out, with the labeling pattern of the gymnomitranes determined by comparison of their NMR spectra with those of the unlabeled compounds. Although the ratio of incorporation of labeled MVL by intact liverworts proved to be low, the acetate-malonate pathway is involved in the biosynthesis of gymnomitranes (932).

Preparative GC of the essential oil of *Reboulia hemisphaerica* led to the isolation of many gymnomitranes, including the new gymnomita-3(15),4-diene (236), together with α -barbatene (234), gymnomitrol (240), (+)-gymnomitr-3(15)-en-

4 α -ol (**243**) gymnomitr-3(15)-en-4-one (**247**), and gymnomitran-4-one (**248**), along with the other sesquiterpenoids, β -acoradiene (**69**), isobazzanene (**260**), β -bazzanene (**261**), and cuparene (**464**), among others (**929**). Gymnomitrol (**240**) was isolated initially from the liverwort, *Gymnomitrion obtusum* (**39**, **40**),

Previously, limonene (**19**) and β -barbatene (**235**) have been found in *Bazzania harpago* (**40**). Further investigation of the volatile components of the same species led to the identification of gymnomitr-3(15),4-diene (**236**), gymnomitr-3-en-15-ol (**237**), gymnomitr-3(15)-en-4 α -ol (**243**) and gymnomitr-3(15)-en-4-one (**247**), together with β -barbatene (**235**) (**490**).

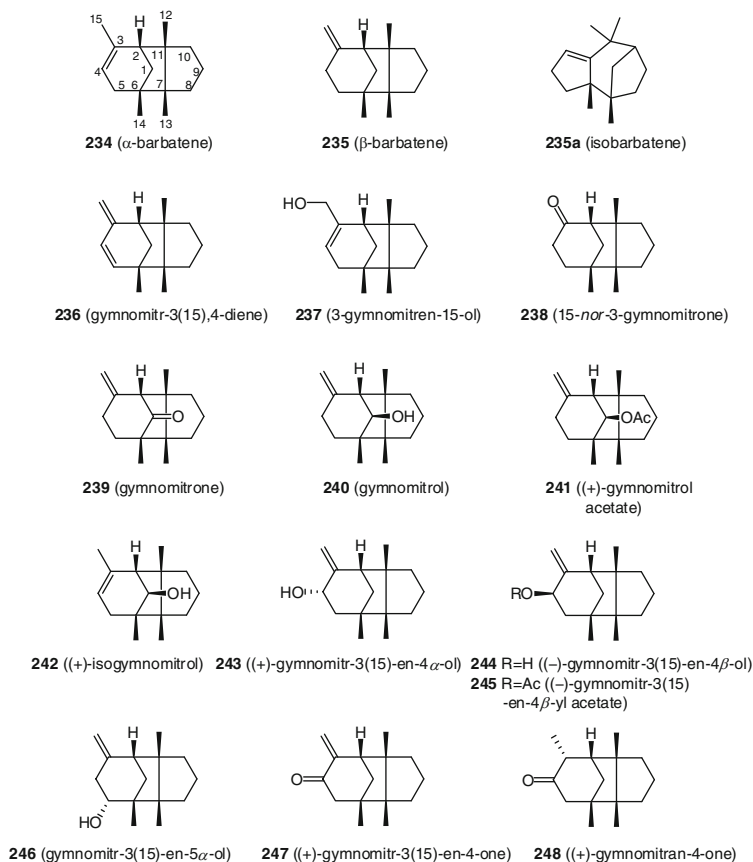
The Malaysian *Jungermannia truncata* was found to biosynthesize a number of *ent*-kaurane diterpenoids (see Sect. 4.3.7) together with two gymnomitranes assigned structurally as 3-gymnomitren-15-ol (**237**) and 15-*nor*-3-gymnomitrone (**238**), as result of extensive 2D-NMR experiments including NOE correlations (**136**). The *n*-hexane and ethyl acetate extracts of different collections of *J. truncata* were re-analyzed by GC/MS to detect both compounds **237** and **238** (**477**). The former compound was found in the New Zealand *Jamesoniella colorata* (**635**), *Jungermannia infusca* (**599**), *Lejeunea aquatica* (**878**), and *Reboulia hemisphaerica* (**492**). Compound **238** is a known synthetic intermediate (**936**).

Reboulia hemisphaerica is a rich source of sesquiterpenoids. Further investigation of the ether extract of *Reboulia hemisphaerica* collected in a different Japanese location led to the isolation of gymnomitrol (**240**) (**436**), which in addition occurs in *Bazzania trilobata* (**582**), *Chiloscyphus*, *Plagiochila* and *Symphyogyna* species (**40**). Also present was (+)-gymnomitr-3(15)-en-5 α -ol (**246**), which has been found in a European specimen of *R. hemisphaerica* (**40**). The ether extract of this same species was reinvestigated by GC/MS to detect the presence of gymnomitrol (**240**) and (+)-gymnomitr-3(15)-en-4 α -ol (**243**) as the major components, together with gymnomitr-3-en-15-ol (**237**) and gymnomitr-3(15)-en-4-one (**247**) (**492**).

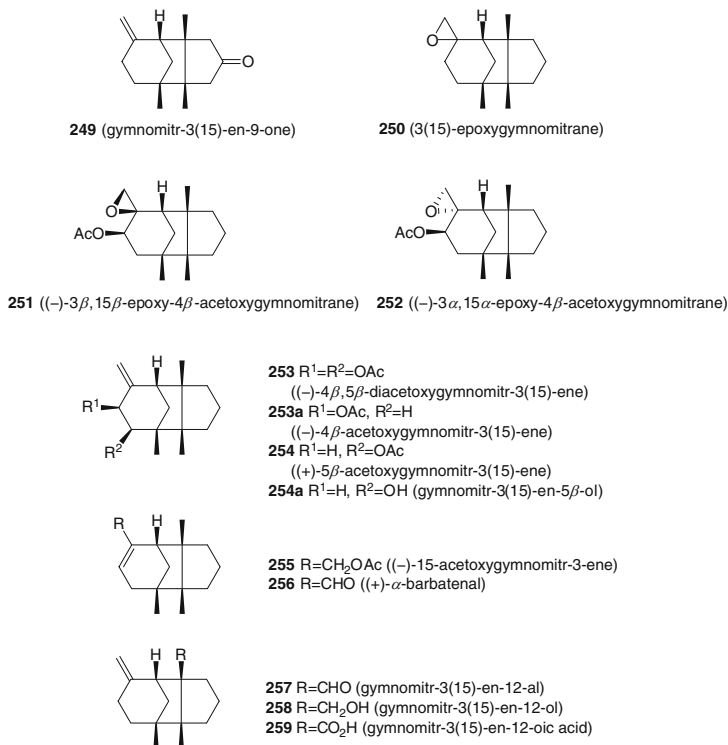
(+)-Gymnomitr-3(15)-en-5 α -ol (**246**) was isolated also from the essential oil of *Cylindrocolea recurvifolia*, belonging to the Cephaloziellaceae, together with β -barbatene (**235**). The structure of compound **246** was established using a combination of NOESY NMR spectroscopic data and X-ray crystallographic analysis. The presence of α -barbatene (**234**) and gymnomitran-3(15),4-diene (**236**) in this same species was detected by means of GC/MS. *Cephaloziella recurvifolia* is the only species belonging to the family Cephaloziellaceae to have been chemically studied, and ledol (**132**), an aromadendrane, was isolated as the major component (see Sect. 4.2.4) (**958**). Compound **246** was isolated from *Isotachis aubertii* with various benzoate and cinnamate derivatives (e.g. **1828**, **1830**, **1834**, **1835**) (**288**).

The ether extract of the European *Plagiochila asplenioides* was investigated to afford β -barbatene (**235**) and (–)-gymnomitr-3(15)-en-4 β -ol (**244**), the C-9 epimer of (+)-gymnomitr-3(15)-4 α -ol (**243**) with a boat conformation. Compound **244** possesses a chair conformation of the cyclohexane ring (**441**, **604**). In addition to compounds **243** and **244**, the ether and ethyl acetate extracts of the Japanese *Plagiochasma pterospermum* were found to contain (+)-gymnomitr-3(15)-en-4-one (**247**) and gymnomitran-4-one (**248**) (**314**).

A new gymnomitrane sesquiterpenoid, gymnomitr-3(15)-en-9-one (**249**), from the ether extract of *R. hemisphaerica*, along with the known gymnomitrol (**240**) and (+)-gymnomitr-3(15)-en-4 α -ol (**243**), has been characterized. The relative and absolute configurations of **249** were determined by interpretation of its 2D-NMR spectra and from the CD spectrum, which showed a negative *Cotton* effect at 312 nm (889). The presence of compound **249** in *Bazzania trilobata* was confirmed by *Scher* and associates (715).



Barbatane-type sesquiterpenoids found in the Marchantiophyta



Barbatane-type sesquiterpenoids found in the Marchantiophyta

Sesquiterpene constituents of *Marsupella emarginata* were studied previously and longipinane sesquiterpenoids were isolated as the major components, along with eremophilane and gymnomitrane sesquiterpenoids (40). Further investigation of the essential oil of the same plant resulted in the isolation of a number of sesquiterpenoids including (-)-3β,15β-epoxy-4β-acetoxygymnomitrane (251), (-)-3α,15α-epoxy-4β-acetoxygymnomitrane (252), (-)-4β,5β-diacetoxygymnomitr-3(15)-ene (253), (+)-5β-acetoxygymnomitr-3(15)-diene (254), and 15-acetoxygymnomitr-3-ene (255). The known β-acoradiene (69), α-barbatene (234), β-barbatene (235), β-bazzanene (261), α-chamigrene (435), β-chamigrene (436), gymnomitr-3(15),4-diene (236), gymnomitr-3(15)-en-4β-ol (244), gymnomitr-4-one (248), 15-nor-3-gymnomitrone (238), and gymnomitr-3(15)-en-4-one (247) were also detected (15, 17). The positions and configuration of two acetoxy groups in the molecule of 253 were assigned by comparison of the NOESY interactions of this compound with those of the known (-)-4β-acetoxygymnomitr-3(15)-ene (245), which was also isolated from the same essential oil. 2D-NMR spectroscopic analysis was used to determine the relative structure of 254, for which the absolute configuration was determined by the formation of gymnomitr-3(15)-en-5β-ol (254a) by alkaline hydrolysis, and the preparation of (-)-gymnomitr-3(15),4-diene (236) by a hydration reaction during the isolation procedure of 254a.

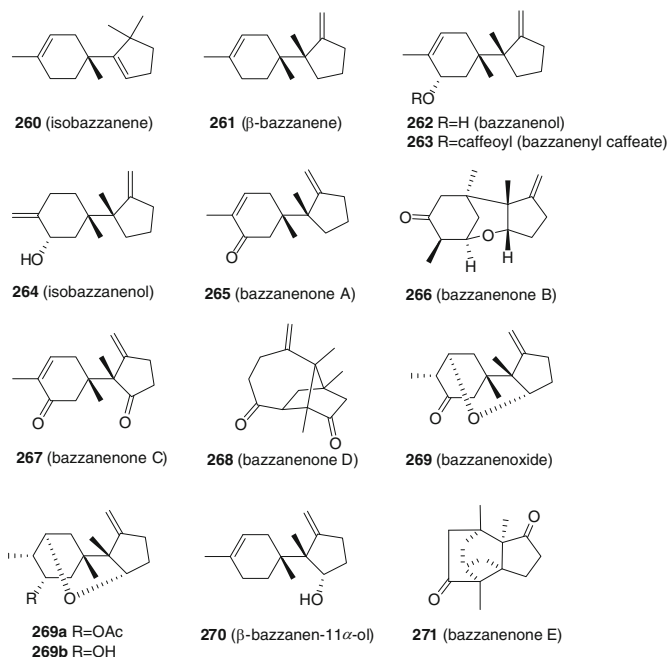
Compound **254a** is an epimer of (–)-gymnomitr-3(15)-en-5 α -ol (**246**), isolated from the liverwort *Cylindrocolea recurvifolia* (958). The structures of **251** and **252** were deduced from their 2D-NMR spectroscopic data. The absolute configuration of (–)-4 β -acetoxygymnomitr-3(15)-ene (**253a**) has been established (17). Epoxidation of **253a** with *m*CPBA gave two epoxides for which the physical and spectroscopic data were identical with those of the natural products, **251** and **252** (17). Compound **255** has been reported as a reaction product of (+)-gymnomitren-15-ol (**237**) (40). Treatment of **255** with potassium carbonate in methanol gave the deacetylated compound, (+)-**237**, which was also isolated and identified in the essential oil of *M. emarginata*. (+)- α -Barbatenal (**256**) was also purified from the same liverwort. Its enantiomer was isolated from the roots of the higher plant, *Joannesia princeps* (7).

Fractionation of the ether extract of an unidentified New Zealand *Heteroscyphus* species led to the isolation of the known gymnomitr-3(15)-en-12-al (**257**) (635), which has been purified from *Marsupella emarginata* (40). Chromatographic work-up of the ether extract of the New Zealand *Chiloscyphus mittenianus* resulted in two gymnomitranes being obtained, (–)-gymnomitr-8(12)-en-15-ol (**258**) and (–)-gymnomitr-8(12)-en-15-oic acid (**259**), which have been found earlier in *Marsupella emarginata* var. *patens* (40). This is the first isolation of gymnomitranes from the species in the genus *Chiloscyphus* (347).

4.2.7 Bazzananes

Bazzanane-type sesquiterpenoids have been found only rarely in Nature. β -Bazzanene (**261**) is the most common component in this series (39, 40).

(–)- β -Bazzanene (**261**), (–)-isobazzanene (**260**), and (–)-isobarbatene (**235a**) of which the latter had not been observed as a natural product previously, were found in the essential oil of the higher plant, *Meum athamanticum*, by capillary column chromatography on cyclodextrin as enantiomers (70% *ee*) of the forms of these substances that occur in liverworts (434). β -Bazzanene (**261**) has been reported in the New Zealand *Bazzania novae-zealandiae* and *B. tayloriana* (72), the French *B. trilobata* (582), and the New Zealand *Plagiochila circinalis* (635). The volatile components of *Bazzania borneensis*, collected in Borneo, were reinvestigated by GC/MS to identify isobazzanene (**260**) (490).



Bazzanane-type sesquiterpenoids found in the Marchantiophyta

The ether extract of *Bazzania pompeana* (Fig. 4.5) was further fractionated to give bazzanene (262) as the major component together with bazzanenyl caffeate (263) as well as isobazzanenol (264), an isomer of 262, as a new compound (84).

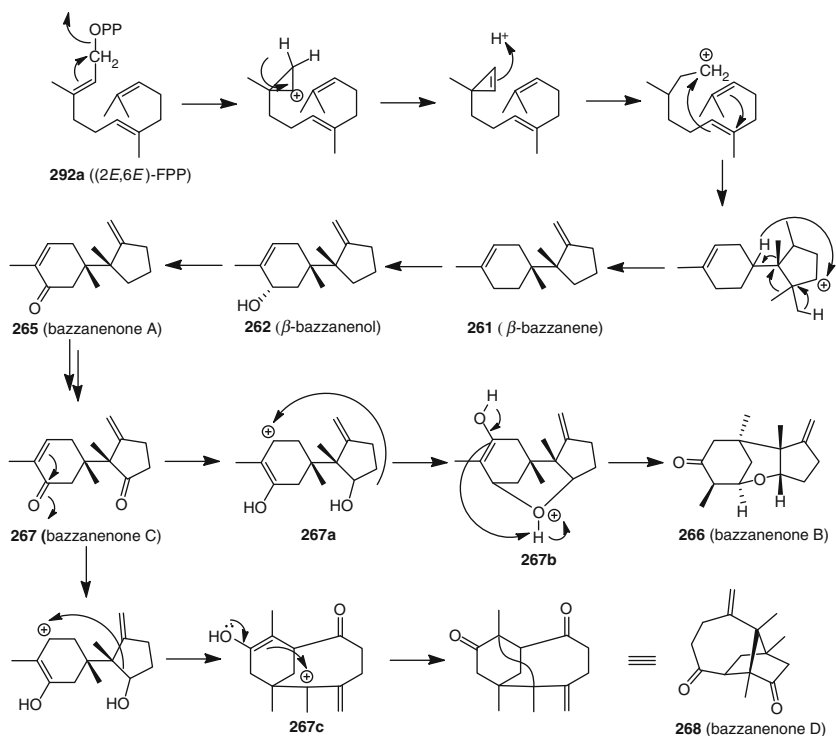


Fig. 4.5 *Bazzania pompeana*

The ether extracts of the New Zealand *Frullania falciloba* and *F. squarrosula* were fractionated to give two the new bazzanane sesquiterpenoids, **265** and **269**, from the former species (613), and the four new bazzananes, **267**, **268**, **270**, and **271**, from the latter (84).

In New Zealand there are 30 species of *Frullania* known (24). Generally, *Frullania* species produce eudesmane and/or eremophilane sesquiterpene lactones, which cause powerful allergenic contact dermatitis, and/or bibenzyl derivatives, with the latter being significant chemical markers for this genus. On the other hand, a New Zealand collection of *F. falciloba* proved to contain neither sesquiterpene lactones nor bibenzyls but rather two new bazzanene sesquiterpenoids, 2-oxobazzanene (= bazzanenone A) (**265**) and bazzanenepoxide (**269**). The structure of **265** was deduced by its formation from bazzanenol (**262**), by treatment with tetrapropylammonium perruthenate. The absolute configurations of **262** and **265** were established from the *Cotton* effect of the *p*-bromobenzoate of **265**. Bazzanenone A (**265**) was reduced with LiAlH_4 to give both bazzanenol (**262**) and its epimer, both of which were esterified with *p*-bromobenzoyl chloride to afford the respective benzoate. The former benzoate showed a negative *Cotton* effect at 243 nm and the latter a positive *Cotton* effect at 239 nm, thus the absolute configuration of the secondary alcohol at C-2 of bazzanenol (**262**) was established as (*S*). Reduction (LiAlH_4) of **269**, followed by acetylation gave the monoacetate **269a** and the unreacted monoalcohol **269b**. The 2D-NMR data, especially the HMBC and NOESY spectra of **269** and **269a**, along with the *Cotton* effect of the parent compound (positive at 295 nm), were used to propose the absolute stereostructure of **269** (613). Previously, *ent*-cyclocolorenone (**126**), β -bazzanene (**261**), a bibenzyl (**1496**), and a phthalide (**1807**) have been reported from *F. falciloba* (40, 502).

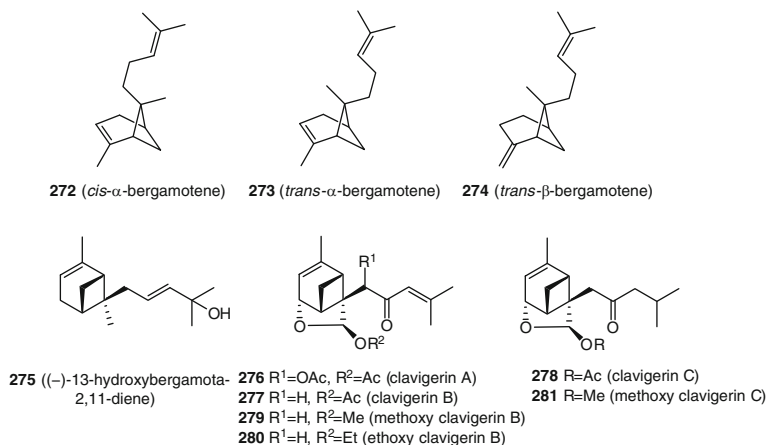
The ether extract of the New Zealand *Frullania squarrosula* was purified by CC to give the new bazzanenones B-D (**266**–**268**), along with the known bazzanenone A (**265**). The relative configuration of bazzanenone B (**266**) was deduced as 6,8-dioxobazzan-11(15)-en-2-one by 2D-NMR observations including the NOESY spectrum, and its absolute configuration was suggested by the presence of a positive *Cotton* effect at 294 nm. Conclusive evidence for the proposed structure of **266** was established by application of the modified *Mosher's* method of the secondary alcohol obtained by the LiAlH_4 reduction of **266**. The relative configuration of bazzanenone C (**267**) was assigned by a comparison of its spectroscopic data with those of **265** and interpretation of its 2D-NMR spectra (HMBC, NOESY). The presence of two ketone groups in bazzanenone D (**268**) was proposed by means of the ^{13}C NMR and IR spectra. Extensive 2D-NMR analysis (HMQC, HMBC, and NOESY) was used to confirm the relative stereostructure of **268** (616). The biogenesis routes of the newly isolated bazzanenones are proposed as shown in Scheme 4.3 (209, 616).



Scheme 4.3 Possible biogenesis pathways for bazzanane-type sesquiterpenoids

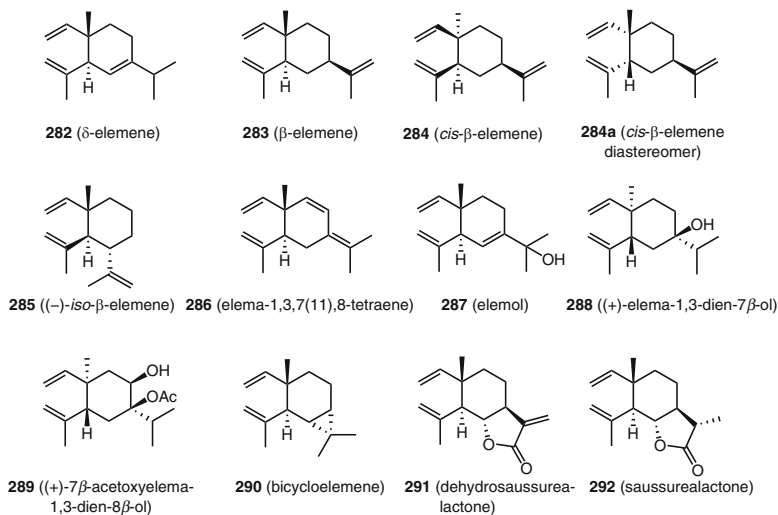
4.2.8 Bergamotanes, Bicycloelemanes, and Elemanes

Bergamotanes are very rare in liverworts. *cis*- (272) and *trans*- α -Bergamotene (273) and *trans*- β -bergamotene (274) have been found in a few liverwort species. *Dumortiera hirsuta* was hydrodistilled to obtain an essential oil, which was analyzed by capillary column chromatography on a cyclodextrin phase to identify (+)-*cis*- α -bergamotene (272) and (+)-*trans*- α -bergamotene (273), showing 100% *ee*. This was the first natural occurrence of an (+)-enantiomer of the bergamotanes (707). The known (–)-13-hydroxybergamota-2,11-diene (275) was obtained from the ether extract of the Argentinean *Gackstroemia decipiens* (252).



Bergamotane-type sesquiterpenoids found in the Marchantiophyta

Fractionation of the New Zealand *Lepidolaena clavigera*, belonging to the Lepidolaenaceae, resulted in the isolation of three new bergamotane sesquiterpenoids. The first of these, clavigerin A (**276**), has an unusual 7-oxatricyclo-[3.2.1.1^{2,8}]nonane ring system (**72**, **616**). Its structure was deduced from its 2D-NMR (COSY, HMBC, NOESY) spectra. Further investigation of the acetonitrile and chloroform extracts of the same liverwort led to the isolation of clavigerins B (**277**) and C (**278**), together with their derivatives **279–281**. The latter compounds are possibly artifacts formed by alcoholysis of the acetoxy acetal group of compounds **277** and **278**, and this could occur either with ethanol used as the extraction solvent, or as a result of reversed-phase chromatography with H₂O-MeOH as solvent mixture. The full structures of **277** and **278** were based on comparison with the NMR spectra of two monoterpenoids, α -pinene (**47**) and verbenol (**47a**), and with NMR data obtained for clavigerin A (**276**). The absolute configurations of **277** and **278** were consistent with that of compound **276** (**656**, **657**).



Elemene- and bicycloelemene-type sesquiterpenoids found in the Marchantiophyta

δ -Elemene (**282**) and β -elemene (**283**) are the most common elemene-type sesquiterpenoids in the liverworts (Table 4.2.). For example, δ -elemene (**282**) and β -elemene (**283**) were identified by GC/MS in the ether extract of the Ecuadorian *Anastrophyllum auritum* (976), and in the essential oils of *Lophozia ventricosa* (486) and of *Bazzania spiralis* and *Heteroscyphus aselliformis* from Borneo (490). β -Elemene (**283**) has also been found among other volatile components of *Drepanolejeunea madagascariensis* (247).

(–)-*cis*- β -Elemene (**284**), a *Cope* rearrangement product of **695**, was obtained from the essential oil of the German *Scapania undulata*, but only in a trace amount. In fact, the thermal isomerization of helminthogermacrene (**695**) was carried out above 350°C to give *cis*- β -elemene (**284**), its diastereomer **284a**, and (–)- β -elemene (**283**), in a ratio of 8:1:0.08 (16).

The reinvestigation of the essential oil of *Saccogyna viticulosa* resulted in the isolation of (–)-*iso*- β -elemene (**285**), which was formed from isogermacrene A (**693**) co-occurring in the same liverwort. The relative structure of **285** was assigned by performing 1- and 2D-NMR experiments (COSY, HMSQC, HMBC). The absolute configuration (5*S*,6*S*,10*S*) was confirmed by chemical correlation between (+)-*iso*-germacrene A (**693**) and its acid-rearranged products, (–)-maaliolide (**723**) and (+)- β -gorgonene (**719**) (276).

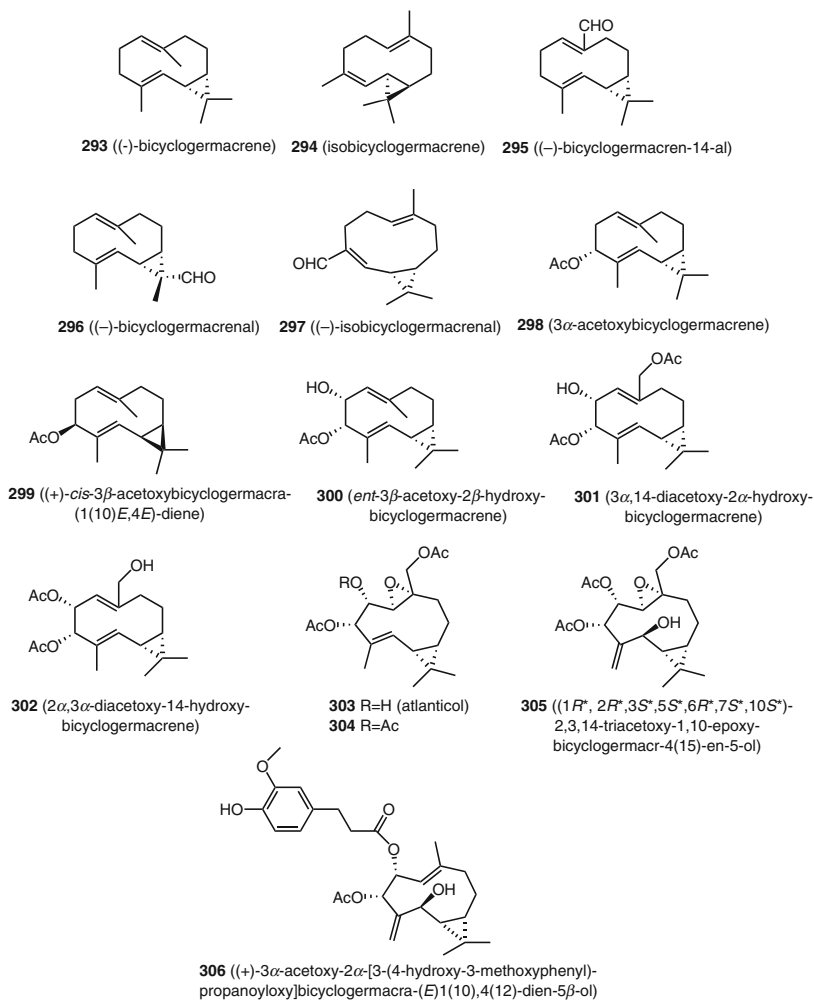
Elemene-1,3,7(11),8-tetraene (**286**) was detected in *Frullania scandens* by GC/MS (78). From the essential oil of the Taiwanese *Lepidozia vitrea*, the two elemene derivatives **288** and **289** were isolated and their structures were elucidated by NMR (inclusive of NOESY) data interpretation. Dehydration of **288** gave (5*R*,10*R*)-elemene-1,3,7-triene and (–)- γ -elemene, which showed the opposite absolute configurations of the C-5 and C-10 chiral centers, when compared with the dehydrated products from (–)-elemol (**287**). Compound **287** has been detected in *Lejeunea* and *Riccardia* species (878). The newly identified elemenes **288** and **289** show the opposite configurations as compared to their forms in higher plants (645).

Bicycloelemene (**290**) has been found in 13 stem-leafy liverworts, as, for example, the Chinese *Cephaloziella recurvifolia* (955). Compound **290** might originate from bicyclogermacrene (**293**) by a *Cope* rearrangement. Two other bicycloelemenes, dehydrosaussurealactone (**291**) and saussurealactone (**292**), occur in *Frullania rostrata* (78).

4.2.9 Bicyclogermacranes and Lepidozanones

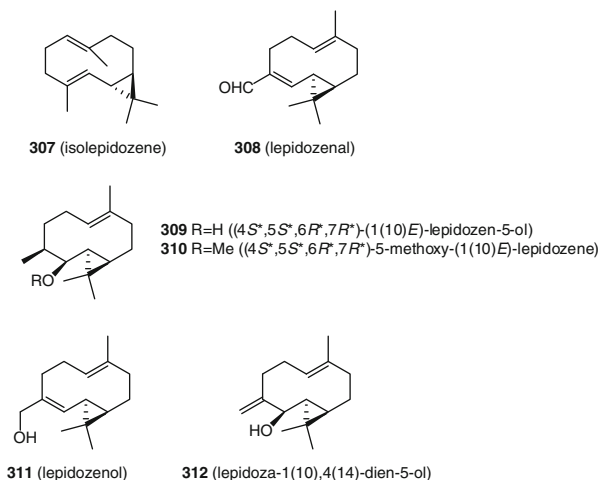
The most abundant sesquiterpene hydrocarbon encountered in liverworts is bicyclogermacrene (**293**), which is one of the most important precursors for many different cyclic sesquiterpenoids, such as the aromadendranes and maalianes. As seen in Table 4.2, 42 species elaborate **293**. Bioactivity-guided fractionation of the ether extract of an unidentified Tahitian *Plagiochila* species using the DPPH radical-scavenging assay resulted in the isolation of bicyclogermacrene (**293**) (701). GC/MS analysis of the ether extract of the New Zealand *Cuspidatula monodon*, *Chiloscyphus allodontus*, and *C. coalitus* indicated the presence of *ent*-bicyclogermacrene (**293**) as the major component (3.8%) (72, 616).

The essential oils of four *Plagiochila* species were analyzed by GC and GC/MS. Among them, *Plagiochila stricta* elaborated bicyclogermacrene (**293**) (3.6–17.3%) and spathulenol (**136**) (2.1–14.2%) (221), with the latter substance originating from compound **293** (870).



Bicyclogermacrene-type sesquiterpenoids found in the Marchantiophyta

The two New Zealand *Frullania* species, *F. atteima* var. *lepidea* and *F. patula* (78) and the German *Scapania undulata* produce isobicyclogermacrene (**294**) (16). Bicyclogermacrene-14-al (**295**) was isolated from the essential oil of *Conocephalum conicum*, along with (–)-isolepidozene (**307**) (543). The same species elaborates (–)-bicyclogermacrenal (**296**) (880). Isobicyclogermacrenal (**297**) was isolated from the ether extract of *Lepidozia vitrea* (871) and *Chiloscyphus setigera*, which is an important chemical marker of *Chiloscyphus* species (347).



Lepidozane-type sesquiterpenoids found in the Marchantiophyta

3 α -Acetoxybicyclogermacrene (**298**) has been found in ten liverwort species, which include the Chinese *Cephaloziella recurvifolia* (955) and *Anastrophyllum donnianum* (139). 3 α -Acetoxybicyclogermacrene (**298**) was also isolated from the ether extract of the Colombian *Plagiochila cristata* and the African-alpine *P. ericicola*. The latter species proved to contain a new bicyclogermacrene, (+)-3 α -acetox-2 α -[3-(4-hydroxy-3-methoxyphenyl)propanoyloxy]bicyclogermacra-(1(10)*E*,4(12))-dien-5 β -ol (**306**), for which the structure was proven after the application of extensive 2D-NMR spectroscopic experiments (COSY and NOE). The dichloromethane extract of the axenic cultured *P. adianthoides* also contains **298** (911).

Chandonanthus hirtellus is a rich source of cembrane and dolabellane diterpenoids (see Sects. 4.3.1 and 4.3.4). Further investigation of the ether extract of the West Malaysian *C. hirtellus* led to the isolation of the new germacrene sesquiterpene acetate, (+)-*cis*-3 β -acetoxybicyclogermacra-(1(10)*E*,4*E*)-diene (**299**), the relative stereochemistry of which was the same as that of (–)-3 α -bicyclogermacrene (**298**) isolated from *Plagiochila*, *Pedinophyllum*, and *Scapania* species (39). However, the sign of the optical rotation of **299** was opposite, indicating that **299** is the enantiomer of **298** (927).

The methanol extract of the cultured cells of *Heteroscyphus planus* was purified by HPLC to afford *ent*-3 β -acetox-2 β -hydroxybicyclogermacrene (**300**). The collection of extensive 2D-NMR data (DEPT, ^1H - ^1H , ^1H - ^{13}C COSY, HMBC, NOESY) was used to establish the structure of **300**. The absolute configuration of **300** was determined by esterification of the secondary hydroxy group at C-2 with (a*S*)- and (a*R*)-2-(2'-methoxy-1'-naphthyl)-3,5-dichlorobenzoic acid (234), as indicated in the absolute configuration of alloaromadendrane sesquiterpene planotriol monoacetate (**179**) (562).

Plagiochila ovalifolia and *P. yokogurensis* were reinvestigated to afford 3 α ,14-diacetox-2 α -hydroxybicyclogermacrene (**301**) and 2 α ,3 α -diacetox-14-hydroxybicyclogermacrene (**302**) (84), which were isolated from *Plagiochila fruticosa* (40).

Atlanticol (**303**) and its analogue **304**, new epoxybicyclogermacrenols, were isolated from the CDCl_3 extract of Scottish and English *Plagiochila atlantica* together with bicyclogermacrene (**293**) and germacrene D (**692**), which were detected by GC/MS of the crude extract. The structure of **303** was elucidated as (1*R*,2*R*,3*S*,4*E*,6*S*,7*S*,10*S*)-3,14-diacetoxy-1,10-epoxybicyclogermacr-4-en-2-ol by means of the preparation of a monoacetate and GC/GC-MS, CIMS, HREIMS, and NMR inclusive of NOE experiments. The absolute configuration was suggested to correspond to the *ent*-series of bicyclogermacranes by analogy with similar compounds that have been found in liverworts. Compound **304** was similar spectroscopically to **305**, indicating that **304** possesses the same structure as **305**, except for the presence of an exocyclic methylene group in place of the vinyl methyl group. Thus, the structure of **304** was assigned as (1*R**,2*R**,3*S**,5*S**,6*S**,7*S**,10*S**)-2,3,14-triacetoxy-1,10-epoxybicyclo-germacr-4(15)-en-5-ol. The configuration of compound **303** was deduced by comparison with the very similar 3 α -acetoxy-2 α -hydroxybicyclogermacrene (**300**), which has been found in a callus culture of *Heteroscyphus planus* (**562**), while the configuration of C-5 in compound **304** was assigned by analogy with compound **306** isolated from *Plagiochila ericicola* (**911**). *Plagiochila aerea* was extracted with deuteriochloroform. The ^1H NMR spectrum of the crude extract indicated the presence of atlanticol (**303**) and its acetate (**305**) (**334**). The essential oil of *Preissia quadrata* produced a main component for which the mass spectrum was found to be similar to that of bicyclogermacrene (**293**). Analysis of the coupling constants of the ring-fused cyclopropane protons suggested the presence of a *trans*-fused bicyclo[8.1.0]undecane system, as in (–)-isolepidozene (**307**), instead of the *cis*-fused system in bicyclogermacrene. Direct comparison of the spectroscopic data of the synthetic **307** with those of the natural product confirmed the structure. Compound **307** has been found in *Frullania tamarisci* and *Scapania aequilobata* (**286**). GC/MS analysis of the ether extract of the Tahitian *Cyathodium foetidissimum* indicated the presence of isolepidozene (**307**) (**493**).

Further investigation of the essential oil of *Lophozia ventricosa* resulted in the identification of lepidozenal (**308**) as a trace constituent (**486**). The ether extract of the Japanese *Dumortiera hirsuta* elaborates 4*S**,5*S**,6*R**,7*R**)-(1(10)*E*)-lepidozen-5-ol (**309**) (**883**), which was isolated from the other liverworts, *Bryopteris filicina*, *Porella swartziana*, and *Trocholejeunea sandvicensis* (**40**).

The ether extracts of the Japanese and German *Conocephalum conicum* and the Japanese *Marchantia tosaensis* were analyzed by GC/MS to identify isolepidozene (**307**) (49.0 and 45.2% in these samples in the total ion chromatograms). *M. tosaensis* contained 1(10)-lepidozen-5-ol (**309**) (**492**), which has been found in *Trocholejeunea sandvicensis* and *Porella swartziana* (**40**).

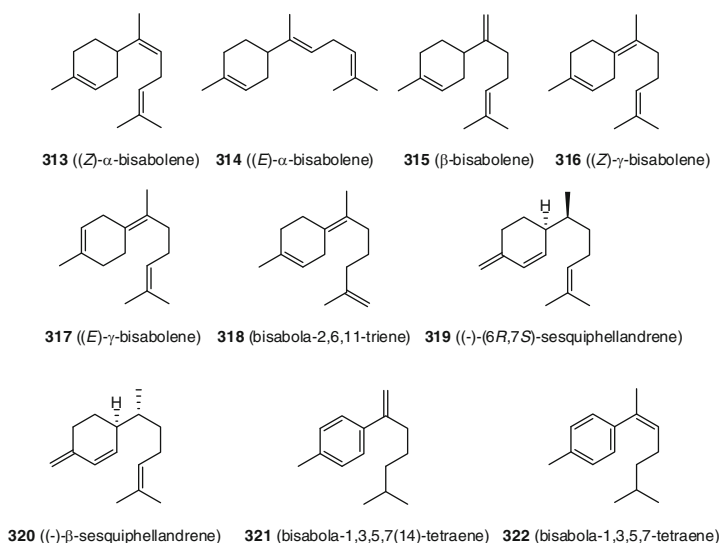
A new lepidozene sesquiterpenoid was isolated from the ether extract of *Porella subobtusa*. The structure of 5-methoxy-(1(10)*E*)-lepidozene (**310**) was determined by the comparison of its 2D-NMR spectroscopic data with those of 1(10)-lepidozen-5-ol (**309**) (**40**) and analysis of the NOESY spectrum (**569**). Two compounds, lepidozenol (**311**) and lepidoza-1(10),4(14)-dien-5-ol (**312**), were isolated from the ether extract of the Costa Rican *Bryopteris filicina* (**604**); however, these compounds were not detected in the same species when collected in Panama (**576**).

4.2.10 Bisabolanes

Twenty-two bisabolanes have been found in liverworts, as shown in Table 4.2. Suspension cultured cells of *Porella vernicosa* were extracted with ether and the crude extract was analyzed by GC/MS to detect β -bisabolene (**315**, 12.7%) (637). The same compound was detected in many stem-leafy liverworts, like *Metacalypogeia cordifolia* (894), *Frullania* (78), *Plagiochila* (221), *Porella* (143), and *Radula* (223), among others.

Dumortiera hirsuta was hydrodistilled to obtain an essential oil that was purified by preparative GC to obtain (*Z*)- γ -bisabolene (**316**). The essential oil was analyzed in a capillary column with a cyclodextrin support material, leading to the identification of *ar*-curcumene (**333**), with a (–)- and (+)-enantiomeric ratio of 87:13% (707).

It is known that *Radula perrottetii* is a rich source of the bibenzyls, 3,5-dihydroxy-2-(3-methyl-2-butenyl)bibenzyl (**1525**), perrottetin A (**1541**), and 2,2-dimethyl-7,8-dihydroxy-5-(2-phenylethyl)chromene (**1542**). Four new bisabolane natural products, bisabola-2,6,11-triene (**318**), bisabola-1,3,5,7(14),11-pentaene (**323**), bisabola-1,3,5,7,11-pentaene (**325**), and 6,7-epoxybisabola-2,11-diene (**326**) have been isolated from the Japanese *Radula perrottetii* together with (*E*)- γ -bisabolene (**317**) and bisabola-1,3,5,7(14),10-pentaene (**324**) (826). The latter two compounds have been isolated from *Biota orientalis* wood (834) and synthesized (923).



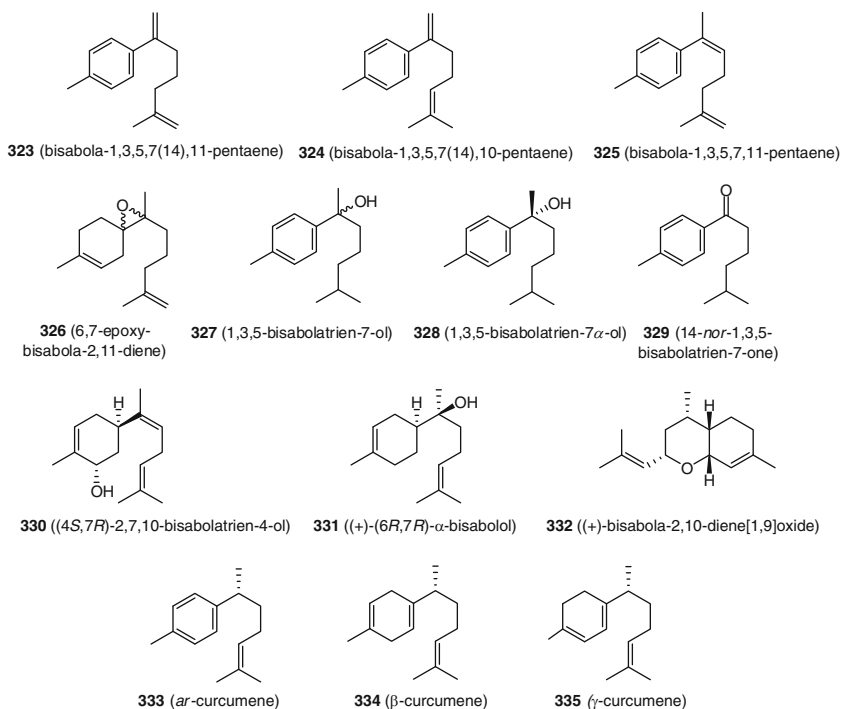
Bisabolane-type sesquiterpenoids found in the Marchantiophyta

Compounds **318**, **323**, **325**, and **326** were isolated for the first time from a liverwort, but these same compounds have been synthesized previously (127, 455, 960, 980). Reinvestigation of the ether extract of the same species by GC/MS confirmed the presence of bisabola-2,6,11-triene (**318**) (492).

Further investigation of the ether extract of the West Malaysian *Chandonanthus hirtellus* led to the isolation of (–)-sesquiphellandrene (**319**) (927), for which the absolute configuration was deduced as (6*R*,7*S*) by comparison with the respective

optical rotation of synthetic (–)- and (+)-sesquiphellandrene (449). The essential oil of *Mannia fragrans* was analyzed by GC using enantioselective GC with modified cyclodextrin as stationary phase to identify (–)- β -sesquiphellandrene (320) and sesquisabinene (932) (542). The former compound was also identified in the ether extract of an unidentified Indonesian *Frullania* species (424).

The hydrodistilled oil of the Taiwanese *Bazzania tridens* was purified by CC to give two aromatic bisabolene-type sesquiterpenoids (321 and 327), and the new norbisabolanone (329), together with norcuparene (469) and humulane oxide (775) (see Sect. 4.2.33) (959). The structures of 327 and 329 were assigned as 1,3,5-bisabotatrien-7-ol and 14-nor-1,3,5-bisabotatrien-7-one by means of 2D-NMR methods.



Bisabolane-type sesquiterpenoids found in the Marchantiophyta

The essential oil of *Plagiochila asplenioides* was purified by preparative GC to obtain two bisabolanones, bisabola-1,3,5,7(14)-tetraene (321) and bisabola-1,3,5,7-tetraene (322), with their structures elucidated by 2D-NMR (COSY, HMBC, HMQC) techniques (14). The ether extract of the New Zealand *Marchantia foliacea* was purified by a combination of CC, Sephadex LH-20, and HPLC to afford the known 1,3,5-bisabotatrien-7 α -ol (328) (347). The ether extract of the large thalloid liverwort *Dumortiera hirsuta* was reinvestigated chemically to give the new bisabolanol 330, the planar structure of which was assigned as 2,7,10-bisabotatrien-4-ol by COSY and HMBC NMR spectroscopy. Oxidation of 330 gave an α,β -unsaturated ketone for which the CD spectrum showed a positive

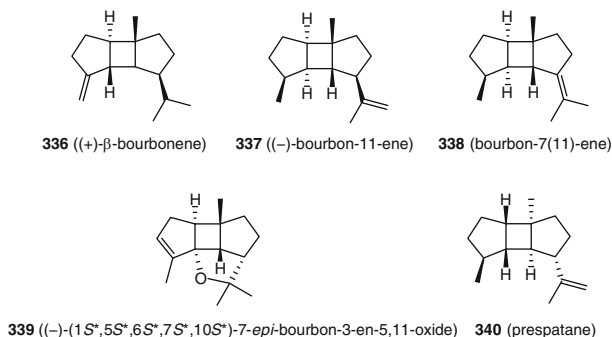
Cotton effect at 244 nm, identical with that of (–)-carvone. Thus, the absolute structure of **330** was determined to be (4*S*,6*R*)-2,7,10-bisabolatrien-4-ol (883).

The ether extract of the European *Pellia epiphylla* was purified by CC and HPLC to yield (+)-(6*R*,7*R*)- α -bisabolol (**331**) (148, 176).

The essential oil obtained by hydrodistillation of *Calypogeia suecica* was analyzed by GC/MS to identify the presence of (*Z*)- γ -bisabolene (**316**), (+)-bisabola-2,10-dien[1,9]oxide (**331**), (+)-*ar*-curcumene (**333**), and (+)- γ -curcumene (**335**). The structure of the bisabolene oxide, compound **332**, was deduced by 2D-NMR spectroscopy (COSY, HMQC, and HMBC) and its relative configuration was assigned by a NOESY experiment. Conclusive evidence for the proposed structure was obtained by chemical correlation between **332** and (–)- β -curcumene (**334**). Hydrogenation of both compounds gave fully saturated bisabolanes, which were analyzed by enantioselective GC using a cyclodextrin phase to show that each product has an opposite configuration. Thus, the bisabolanes **333** and **335** isolated from this liverwort have the same absolute configuration (934). It is noteworthy that the Ecuadorian *Anastrophyllum auritum* biosynthesizes (–)-*ar*-curcumene (**333**) (976), which is the enantiomer of curcumene isolated from *Calypogeia suecica*.

4.2.11 Bourbonanes

β -Bourbonene (**336**) has been identified in nine liverwort species. The volatile components of *Bazzania borneensis* collected in Borneo were reinvestigated to identify β -bourbonene (**336**) (490). Application of the HS-SPME (head space-solid phase microextraction) technique coupled with GC/MS analysis led to detection of a volatile component of *Drepanolejeunea madagascariensis*, identified as β -bourbonene (**336**) (247).



Bourbonane-type sesquiterpenoids found in the Marchantiophyta

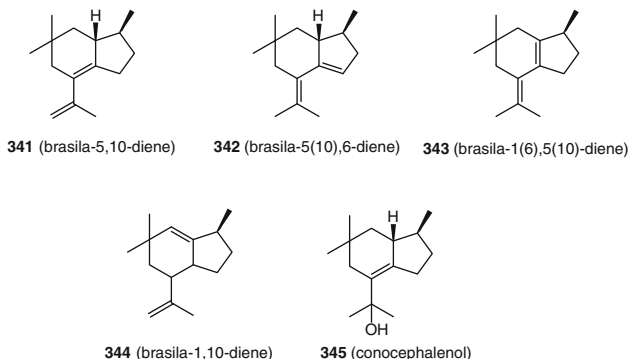
(+)- β -Bourbonene (**336**) was isolated from *Lepidozia reptans* (681). In turn, bourbon-11-ene (**337**) was found in *Kurzia* and *Mylia* (922), *Jungermannia*, and *Pellia* species (492, 494), and its (–)-enantiomer (**337**) was also isolated from *Calypogeia* (933), *Frullania* (644), and *Tritomaria* species (928).

Symphyogyna brasiliensis elaborates bourbon-7(11)-ene (**338**) (492). 7-*epi*-Bourbon-3-en-5,11-oxide (**339**) was isolated from the essential oil of *Mylia taylorii* and detected in the Taiwanese *M. nuda* and its structure elucidated as the first oxacylic sesquiterpene with the formerly unknown 7-*epi* configuration by 2D-NMR spectroscopic analysis. The same compound has also been detected in the essential oil of the Austrian liverwort *Kurzia trichoclados* belonging to the Lepidoziaceae family (922).

The cultured cells of *Ptychathus striatus* were extracted and fractionated by CC to give prespatane (**340**) (565), striatol (**809**), and kelsoene (**915**) (396). A biosynthesis study on (–)-prespatane (**340**) was performed by Nabeta and associates using cultured cells of *Ptychantus striatus* and ²H- and ¹³C-labeled mevalonate. Prespatane is postulated to be biosynthesized from a (7*S*)-germacradienyl cation by means of a guaianyl cation. One proton at the C-1 position of FPP was lost during the third cyclization of the guaianyl cation (567).

4.2.12 Brasilanes

A European sample of *Conocephalum conicum* elaborated the brasilane sesquiterpenoid, conocephalenol (**345**), but an Asian collection of the same species did not contain this compound. The absolute configuration of compound **345** was established by the total synthesis of an enantiomer (40). Ludwiczuk and colleagues reconfirmed the presence of **345** in European collections (493). The essential oil obtained from the German *Conocephalum conicum* was purified by preparative GC to give brasila-5,10-diene (**341**), brasila-5(10),6-diene (**342**), and brasila-1(6),5(10)-diene (**343**). Dehydration of conocephalenol (**345**) with phosphoryl chloride afforded the dehydrated products **341–343**, indicating that the structures of the isolated compounds are correct and have the same stereochemical correlations (543). It is interesting to note that the red alga *Laurencia implicata* also produces the same brasilane sesquiterpenoid (841).



Brasilane-type sesquiterpenoids found in the Marchantiophyta

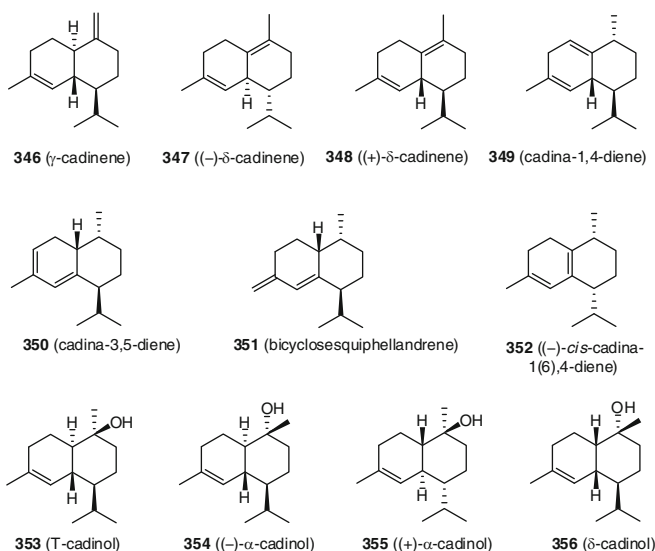
Tori et al. achieved the total synthesis of conocephalenol (**345**) from 1-methyl-7,7a-dihydroindan-5(6*H*)-one in 20 steps and the natural product was obtained by

resolution of an alcohol intermediate obtained from a racemic trimethyl hydrindone in 14 steps (845). A shorter total synthesis of (+)-conocephalenol (345) was performed by Cossy and associates in seven steps, with (*R*)-pulegone as the starting material, in an overall yield of 15% (166).

An Ecuadorian specimen of *Noteroclada confluens* produced brasila-5(10), 6-diene (342), brasila-1,10-diene (344), pacifigorgia-1,10-diene (836), and paci-figorgia-1(6),10-diene (837), together with bicyclogermacrene (293) (492).

4.2.13 Cadinanes, Amorphanes, and Muurolanes

Cadinanes and their stereoisomers, the amorphanes, are relatively widely distributed in liverworts, but the other stereoisomers, the muurolanes, are rare within this plant group. Among the cadinanes, γ -cadinene (346), (–)-(347), and (+)- δ -cadinene (348) are the most common in the liverworts (Table 4.2).



Cadinane-type sesquiterpenoids found in the Marchantiophyta

The essential oil of *Preissia quadrata* was analyzed by GC/MS using a cyclodextrin column to detect (–)- δ -cadinene (347) and (–)- γ -amorphene (368) (433). It is noteworthy that the enantiomer of 347, (+)- δ -cadinene (348) was present in a *n*-hexane extract of *Marchantia emarginata* subsp. *tosana* (347).

(–)-(1*R*,7*S*,10*R*)-Cadin-3,5-diene (350) was isolated from the volatile of the higher plant, manuka (*Leptospermum scoparium*), while its enantiomer was present in the German liverwort *Conocephalum conicum* (541). The volatile components of an unidentified *Pallavicinia* species from Borneo were investigated to identify compound 350 and bicyclosquisphellandrene (351) (490).

The essential oil of the European and American *Bazzania trilobata* obtained by hydrodistillation was analyzed by GC and GC/MS. Forty-four and twenty-nine

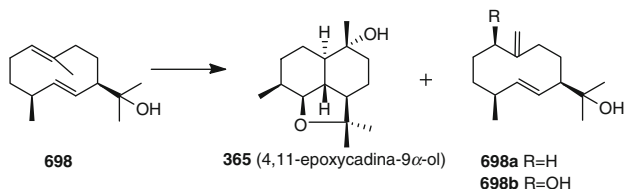
sesquiterpene constituents were identified, respectively, from these specimens (930). Among these, two compounds, (–)-*cis*-cadin-1(6),4-diene (352) and (+)-*trans*-dauca-4(11),8-diene (532) (see Sect. 4.2.22) were isolated by preparative GC as new compounds. The structure of 352 was deduced by ¹H- and ¹³C NMR spectroscopy and comparison of such data with those obtained for the C-7 epimer, (–)-*trans*-cadin-1(6),4-diene, isolated from manuka essential oil (541), in addition to preparation of the co-occurring *cis*-calamenene (404).

T-Cadinol (353) and α-cadinol (354) are distributed among a limited number of species, including those in the genera *Calypogeia* (933), *Frullania* (644), *Plagiochila* (221), and *Jungermannia* (494). The latter compound occurs in the forms (–)-(354) and (+)-(355) in *Calypogeia muelleriana* (933) and *Jackiella javanica* (608).

Wu reported that Taiwanese *Mannia supilosa* produced compounds 359–362 in their enantiomeric form (949). Later, this plant name was changed from *M. supilosa* to *Reboulia hemisphaerica* (935). The ethyl acetate extract of the *R. hemisphaerica* was purified by CC to afford cadina-4,11-dien-14-al (359) and cadina-4,11-dien-14-ol (360) as major components. The assignment of the conjugated functional group at C-4 as well as the cadinane skeleton was deduced by ¹H-¹H and ¹³C-¹H COSY NMR experiments. The *antiperiplanar* relationships of the four protons at C-1, C-6, C-7, and C-10 were indicated by the large ¹H NMR coupling constants and further evidence for the relative configuration was obtained by NOE experiments. 14-Acetoxycadin-4,11-diene (361) and cadina-4,11-dien-14-oic acid (362) were also isolated from the same plant collected in a different locality. An enantiomer of compound 362 was named pernetic acid (348). The absolute configuration of pernetic acid with a β-isopropenyl group was determined from its *Cotton* effect. The CD spectrum of 362 isolated from the liverwort showed the inverse *Cotton* effect to pernetic acid, indicating that this isolate is the mirror image. Three other cadinanes (359–361) were found to possess the (1*R*,6*S*,7*S*,10*S*)-configuration (935).

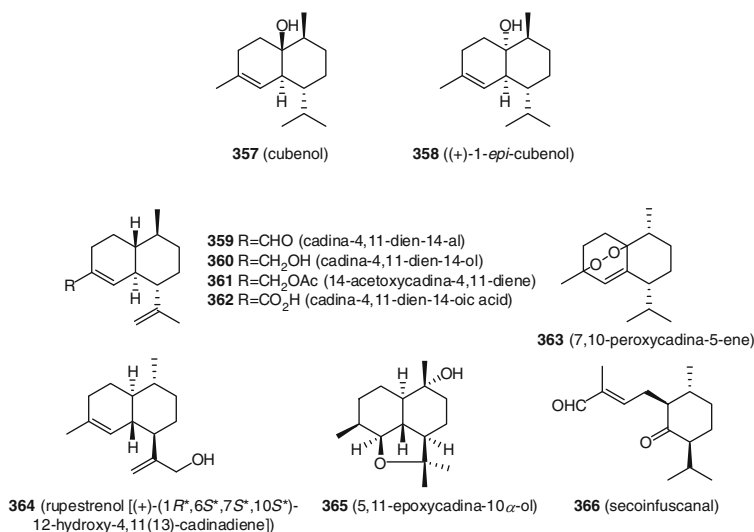
Nagashima *et al.* reported the presence of 7,10-peroxycadin-5-ene (363) in the French *Bazzania trilobata* (582). *Plagiochasma rupestre*, also collected in France, has been studied chemically by Harrison and colleagues and they found longipinane and elemene sesquiterpenoids, and the hopane triterpenoid, α-zeorin (1437), along with flavone methyl ether (299). Reinvestigation of the ether and methanol extracts of the same species collected in Argentina resulted in the isolation of a new cadinane sesquiterpene alcohol, named rupestrenol (364). Oxidation of 364 with pyridinium dichromate gave an aldehyde, which was treated with 2,4-dinitrophenylhydrazine to afford its hydrazone. The conclusive structure of 364 was established by a combination of the 2D-NMR spectroscopic and X-ray crystallographic analysis of the hydrazone (97).

Further investigation of the chemical constituents of the Japanese and Taiwanese *Ptychanthus striatus* resulted in the isolation of the new cadinane epoxide 365 from the specimen collected in Japan, for which the stereochemistry was established by the analysis of NOE correlations and X-ray crystallographic analysis. In addition, tritomarene (915) was isolated from the Taiwanese specimen (325). Toyota *et al.* reported the formation of cadinane epoxide (365) from germacra-1(10),5-dien-11-ol (698) and two additional germacradienes (698a, 698b), as shown in Scheme 4.4 (883).



Scheme 4.4 Formation of a cadinane derivative from a germacrane-type sesquiterpene alcohol

Jungermannia infusca produces a secocadinane, the sesquiterpene aldehyde, secoinfuscanal (**366**), and its absolute structure was assigned by 2D-NMR spectroscopy and the back octant rule applied to the first positive *Cotton* effect (296 nm) in the CD spectrum (600).

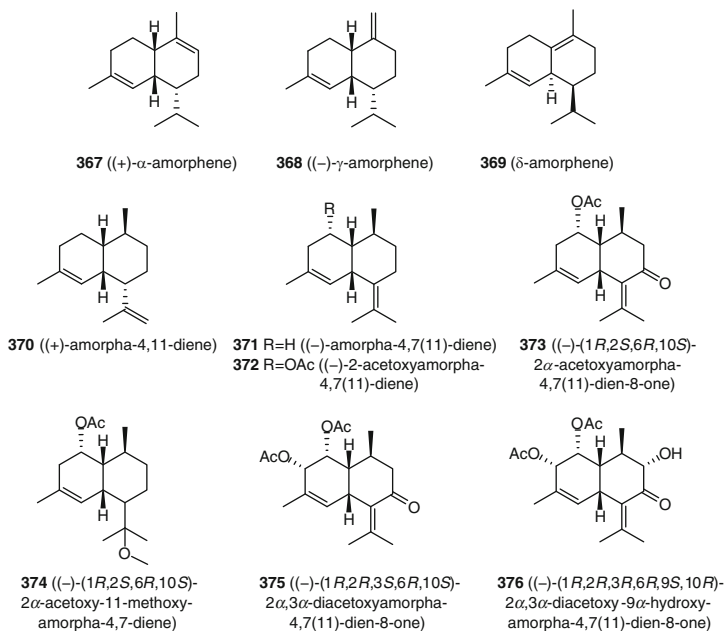


Cadinane-type sesquiterpenoids found in the Marchantiophyta

Three amorphane sesquiterpene hydrocarbons, α - (**367**), γ - (**368**), and δ -amorphene (**369**), were found in several *Jungermanniales* species (Table 4.2), among which the (+)-enantiomer (**367**) of α -amorphene and the (–)-enantiomer of γ -amorphene (**368**) have been isolated from *Scapania undulata* (16) and *Preissia quadrata* (433), and detected in an unidentified Indonesian *Frullania* species (424).

The three amorphanes, (+)-amorpho-4,11-diene (**370**), (–)-amorpho-4,7(11)-diene (**371**), and (–)-2-acetoxymorpho-4,7(11)-diene (**372**), were isolated from the Austrian *Marsupella aquatica* (17). Further investigation of the essential oil of this same liverwort resulted in the isolation of nine amorphane sesquiterpenoids, for which the structures were established as (+)-(1*R*,6*S*,10*S*)-7 β -hydroxymorpho-4,11-diene (**377**), (+)-(1*R*,2*S*,6*R*,8*S*,10*S*)-2,8-epoxymorpho-4,7(11)-diene (**378**), (+)-(1*S*,5*S*,6*R*,9*R*,10*R*)-5,9-epoxymorpho-3,7(11)-diene (**379**), (–)-(1*S*,6*S*,9*R*,10*R*)-9 α -hydroxymorpho-4,7(11)-diene (**380**), (–)-(1*R*,6*S*,9*R*,10*R*)-3 α -hydroxymorpho-4,7(11)-diene (**381**), (–)-(1*R*,3*R*,6*S*,10*S*)-3 α -acetoxymorpho-4,7

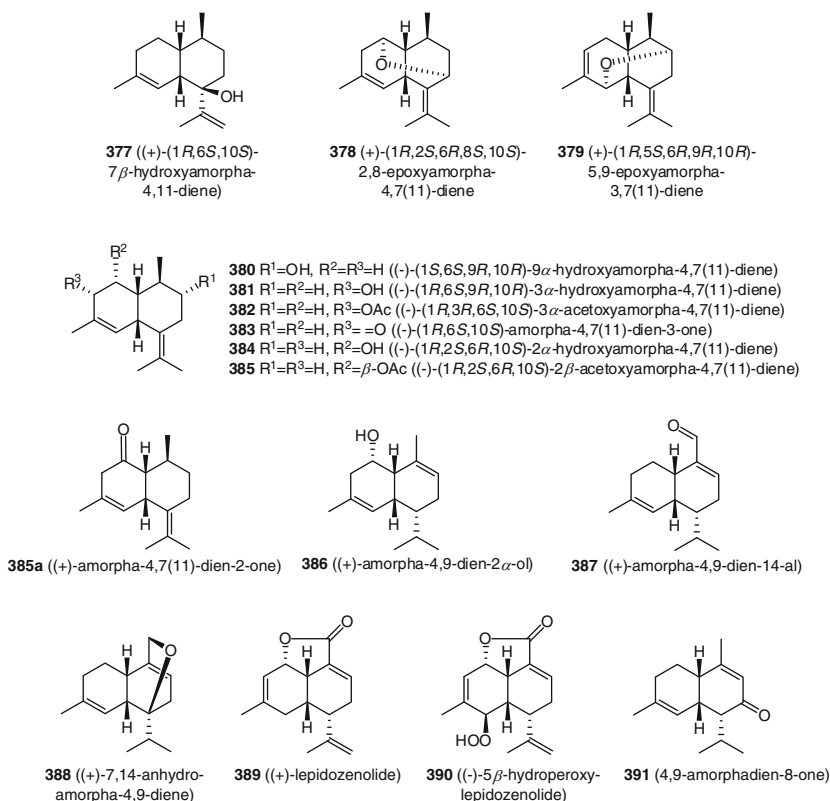
(11)-diene (**382**), (–)-(1*R*,6*S*,10*S*)-amorpha-4,7(11)-dien-3-one (**383**), (–)-(1*R*,2*S*,6*R*,10*S*)-2*α*-hydroxyamorpha-4,7(11)-diene (**384**), and (–)-(1*R*,2*R*,6*R*, 10*S*)-2*β*-acetoxyamorpha- 4,7(11)-diene (**385**). These were accompanied by the common sesquiterpene hydrocarbons, β -acoradiene (**69**), calarene (**109**), anastreptene (**122**), α -barbatene (**234**), β -barbatene (**235**), α -isobazzanene (**260**), β -elemene (**283**), cadina-1,4-diene (**349**), chamigrene (**435**), α -copaene (**455**) (obtained in trace amounts), β -copaene (**456**), δ -cuprenene (**468**), α -longipinenene (**783**), and cyclomyltaylane (**819**) (**19**).



Amorphane-type sesquiterpenoids found in the Marchantiophyta

The absolute configurations of **377** and **380** were determined by a comparison of the fully hydrogenated products of (–)-amorpha-4,7(11)-diene (**371**) with those of (+)-**377** using enantioselective GC on a modified cyclodextrin stationary phase. The absolute configuration of (+)-(1*R*,6*S*,7*S*,10*S*)-1-*epi*-cubenol (**358**) was also assigned by the treatment of **358** with Amberlyst[®] resin to afford (+)-cadina-1,4-diene (**349**) and (+)-*trans*-calamenene (**405**). Direct hydrogenation of **381** gave identical products to those obtained for **377** and **380**. Dehydration of **381** afforded (+)-amorpha-2,4,7(11)-triene, for which the relative configuration was determined using its NOESY spectrum. Fully hydrogenated products of the triene were identical to those obtained from **371**, **377**, **380**, and **381**. Thus, the triene was assigned with the (1*S*,6*S*,10*S*)-configuration. Hydrolysis of **382**, which is an acetate of **381**, gave a secondary alcohol with the same spectroscopic data as those of **381**. Treatment of **381** with PDC furnished a ketone with spectroscopic data identical to those of **383**, indicating that the latter compound has the (1*R*,6*S*,10*S*)-configuration. Direct hydrogenation of **378** gave products identical to those obtained from (–)-**371** as well as from **377**, **380**, and **381**, suggesting that **378** possesses the

(1*R*,2*S*,6*R*,8*S*,10*S*)-configuration. Compound **378** was treated with Amberlyst[®] resin to give cadalene (**421**) and α -calacorene (**419**). Hydrogenation of **379** afforded the same products as **378**, confirming the (1*S*,5*S*,6*R*,9*R*,10*R*)-configuration of this compound. In turn, the absolute configuration of **384** was deduced by the same method as mentioned above. Moreover, the absolute configuration of **385** was determined by the formation of (+)-amorpha-4,7(11)-dien-2-one (**385a**) from **385** and (–)-2-acetoxyamorpha-4,7(11)-diene (**372**) by hydrolysis, followed by oxidation by PDC. The co-occurrence of compounds **370–372**, **377–385** with (–)-(1*R*,2*S*,6*R*,10*S*)-2 α -acetoxy-11-methoxyamorpha-4,7-diene (**374**) and (–)-(1*R*,2*S*,6*R*,10*S*)-2 α -acetoxyamorpha-4,7(11)-dien-8-one (**373**) suggested that the Austrian *M. aquatica* contains amorphanes as the major constituents, along with traces of the cadinane/murolane, (+)-1-*epi*-cubenol (**358**), a few barbatanes, and longipinanes (**19**).



Amorphane-type sesquiterpenoids found in the Marchantiophyta

The Scottish *Marsupella emarginata* var. *aquatica* was investigated chemically and the four oxygenated amorphane sesquiterpenoids, (–)-(1*R*,2*S*,6*R*,10*S*)-2 α -acetoxyamorpha-4,7(11)-dien-8-one (**373**), (–)-(1*R*,2*S*,6*R*,10*S*)-2 α -acetoxy-11-methoxyamorpha-4,7-diene (**374**), (–)-(1*R*,2*R*,3*S*,6*R*,10*S*)-2 α ,3 α -diacetoxy-4,7(11)-dien-8-one (**375**), and (–)-(1*R*,2*R*,3*R*,6*R*,9*S*,10*R*)-2 α ,3 α -diacetoxy-9 α -hydroxyamorpha-4(7),11-dien-8-one (**376**) were identified. The relative configuration

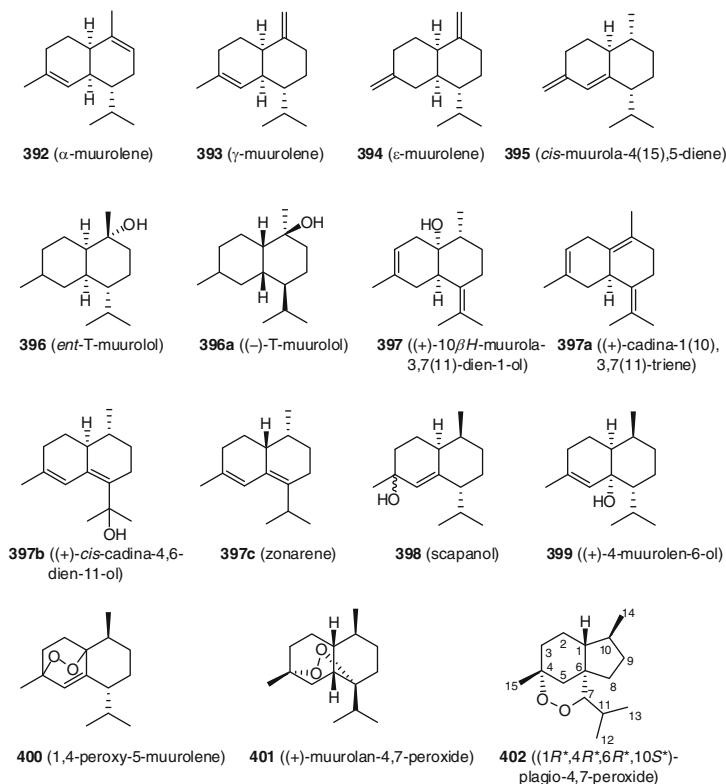
of the isolated compounds was deduced by 2D-NMR spectroscopic data interpretation. The absolute configuration of **375** could be determined from the benzoate rule, based on the *Cotton* effect of the dibenzoate prepared from **375** by methanolysis. The absolute configurations of the other compounds in the amorphene series were deduced as a result of their co-occurrence with **375** (465).

From the essential oil of the Taiwanese *Lepidozia fauriana*, the three amorphanes **386–388** were isolated and their structures elucidated by 2D-NMR (HMQC, HMBC, NOE, NOESY) spectroscopic measurements. Their absolute configurations were confirmed by partial hydrogenation to give (+)- α -amorphene (**367**) (435), indicating that compounds **386–388** possess the opposite configuration as compared to when they occur in higher plants (645).

Lepidozenolide (**389**) and 5 β -hydroperoxyepidozenolide (**390**), previously reported (40), were identified as the minor components of the Taiwanese *Lepidozia fauriana* and *L. vitrea* by GC/MS and 2D-NMR spectroscopy (745). The structure elucidation of both compounds was reported in detail by the same group (747). Conclusive evidence for the structure of the peroxide **390** was obtained from its X-ray crystallographic analysis. The structure of the deperoxy derivative **389** was assigned from the 2D-NMR data (747).

Purification of the ether extract of the New Zealand *Lepidozia setigera* gave a new 4,9-amorphadien-8-one (**391**), for which the complete structure was deduced by 1D- and 2D-NMR (COSY, HMBC, NOESY) spectroscopy as well as molecular operating environment (MOE) calculations. The absolute configuration of **391** was determined by the positive and the negative *Cotton* effects at 238 nm and 327 nm in the CD spectrum (347).

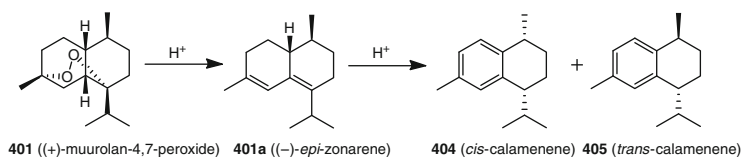
α - (**392**), γ - (**393**), and ϵ -Muurolene (**394**) were found in several stem-leafy liverworts. *Ludwiczuk* and associates analyzed the volatile principles of an unidentified *Jungermannia* species by GC/MS to identify *cis*-muurolo-4(15),5-diene (**395**) and T-muurolol (**396**) (494). An enantiomer of **396** was isolated from *Scapania undulata* (569). Compound **396** was also detected in *Calypogeia muelleriana* (933). The essential oil of the German *Calypogeia fissa*, obtained by hydrodistillation, contained (+)-10 β H-muurolo-3,7(11)-dien-1-ol (**397**), the structure of which was established using a combination of its NMR spectroscopic data and by chemical reaction. Thus, dehydration of **397** with thionyl chloride in pyridine gave only (+)-cadina-1(10),3,7(11)-triene (**397a**). Treatment of **397** with Amberlyst[®] resin in *n*-hexane afforded four compounds, (+)-*cis*-cadina-4,6-dien-11-ol (**397b**), (+)-*cis*-calamenene (**404**), and (–)-*trans*-calamenene (**405**) together with **397a**. The absolute configuration of **397–397b** was based on a correlation reaction with (+)- δ -cadinene (**348**). After catalytic hydrogenation of **397a** and **348**, four hydrogenation products of **397a** were shown to have the same GC/MS characteristics and the same retention times on an achiral phase but different retention times on a chiral cyclodextrin GC phase, when compared to the hydrogenation products of **348**. Thus, the relative configuration of these saturated cadinenes might be identical but the absolute configuration was opposite (931). The ether extract of *Mastigophora diclados* was analyzed by GC/MS to detect zonarene (**397c**) (425).



Muurolane-type and related sesquiterpenoids found in the Marchantiophyta

Scapania undulata is a rich source of both sesquiterpenoids and diterpenoids. Three new cadinanes, *ent*-T-muurolol (**396**), scapanol (**398**), and (+)-4-muurolen-6 α -ol (**399**) were isolated from this species together with *ent*-1-*epi*-cubenol (**358**). The physical and spectroscopic data of **396** were identical to those of (-)-T-muurolol (**396a**), except for the sign of the optical rotation. Thus, **396** was assigned as *ent*-T-muurolol, which is the first record of its isolation from a liverwort. Analysis of the 2D-NMR spectroscopic data of **399** indicated its identity as 4-muurolen-6 α -ol, after comparison with analogous information for *ent*-1-*epi*-cubenol (**358**). Further evidence for the structure of **399** was deduced by the formation of *trans*-calamenene (**405**) by dehydration, employing NOE experiments, pyridine-induced solvent shifts, and a NMR shift experiment using Eu(fod)₃. The similarity of the analytical data of scapanol (**398**) to those of **396** and analysis of the ¹H and ¹³C NMR, COSY, and HMBC data also suggested that **398** is a cadinane derivative, with a tertiary alcohol at C-4. The stereochemistry of **398** was assigned tentatively as a result of its co-occurrence with **398**, **399**, and *ent*-1-*epi*-cubenol (**358**) (**577**). A Belgian *S. undulata* sample also elaborated 1,4-peroxy-5-muurolene (**400**) (**569**).

The essential oil of *Plagiochila asplenioides* was purified by preparative GC to obtain muurolan-4,7-peroxide (**401**), for which the stereostructure was established based on 2D-NMR experiments (COSY, HMBC, HMQC, NOESY).

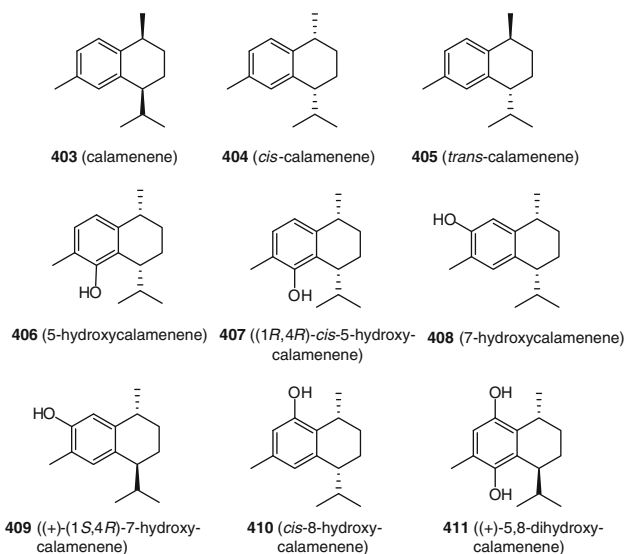


Scheme 4.5 Formation of zonarene and calamenenes from muurola peroxide

The absolute configuration was elucidated by comparison with four fully saturated diastereoisomeric amorphanes of **401** with the fully hydrogenated products of (–)-amorpha-4,7(11)-diene (**371**) (*14*), a compound isolated from *Marsupella aquatica* (*17*) by enantio-selective GC. Also formed by hydrogenation were (–)-*epi*-zonarene (**401a**) along with (+)-*trans*-calamenene (**405**) and (–)-*cis*-calamenene (**404**), with the last two-mentioned compounds obtained as minor components (Scheme 4.5). In addition to the above compound, an *abeo*-muurolane- or *abeo*-amorphane-type sesquiterpene named plagio-4,7-peroxide (**402**) was isolated and its structure was elucidated by 2D-NMR (COSY, HMBC, HMQC) data interpretation. (+)-Plagio-4,7-peroxide (**402**) has been reported by Nagashima and associates from the ether extract of this same liverwort (*604*) and from *P. ovalifolia* (*84*). This peroxy compound possesses the same skeleton as 7,10-peroxycadina-5-ene (**363**) (*582*).

4.2.14 Calamenanes

(1*S*,4*S*)-Calamenene (**403**) is distributed in eight species belonging to the Jungermanniales, as shown in Table 4.2.



Calamenane-type sesquiterpenoids found in the Marchantiophyta

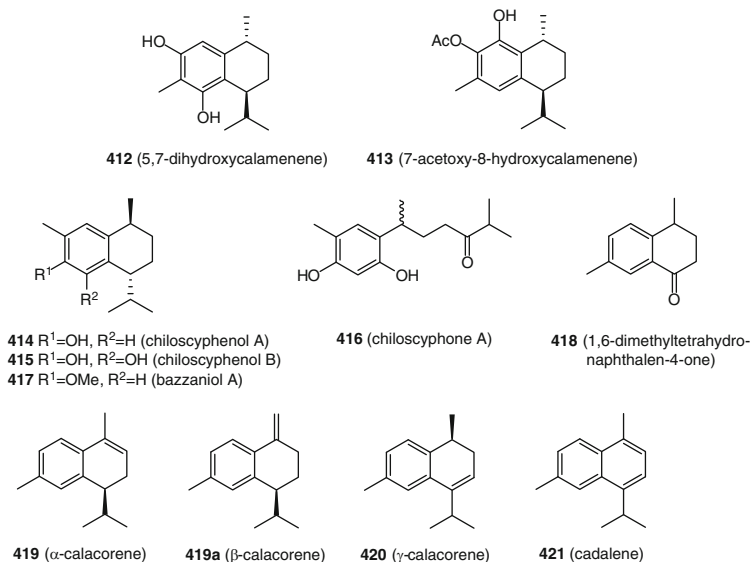
Further fractionation of the French *Bazzania trilobata* resulted in the isolation of (1*R*,4*R*)-calamenene (**404**), (1*R*,4*R*)-*cis*-5-hydroxycalamenene (**407**), and *cis*-

8-hydroxycalamenene (**410**) ([582](#)). *Lepidolaena hodgsoniae* elaborates (1*R*,4*R*)-calamenene (**403**) as the major component ([101](#)). In order to clarify the absolute configurations of calamenene and 5-hydroxycalamenene, X-ray crystallographic analysis of the *p*-bromobenzoate prepared from **407** was carried out. The results showed that the previously assigned (1*S*,4*S*)-*cis*-5-hydroxycalamenene (**40**) should be revised to (1*R*,4*R*)-*cis*-5-hydroxycalamenene (**407**).

5-Hydroxycalamenene (**406**) and 7-hydroxycalamenene (**408**) were isolated from *Bazzania trilobata* ([582](#), [715](#)). 7-Hydroxy- (**408**) and 5,7-dihydroxycalamenene (**412**) were isolated from *Dumortiera hirsuta* ([487](#)).

Fractionation of the ether extract of the Malagasy *Bazzania nitida* led to the isolation of the known (+)-(1*S*,4*R*)-7-hydroxycalamenene (**409**) ([289](#)), which was found in cultured cells of the liverwort *Heteroscyphus planus* (**40**).

A new calamenene, (+)-5,8-dihydroxycalamenene (**411**), was isolated from the ether extract of *Heteroscyphus planus*, together with (+)-(1*S*,4*R*)-7-hydroxycalamenene (**409**). A combination of IR, UV, and ¹H NMR spectroscopic data and the formation of 5,8-naphthoquinone by autoxidation was used to confirm the structure of **411**. Its absolute configuration was deduced to be (1*S*) and (4*R*) by consideration of its co-occurrence with (+)-(1*S*,4*R*)-7-hydroxycalamenene (**409**) in the same liverwort ([310](#)).



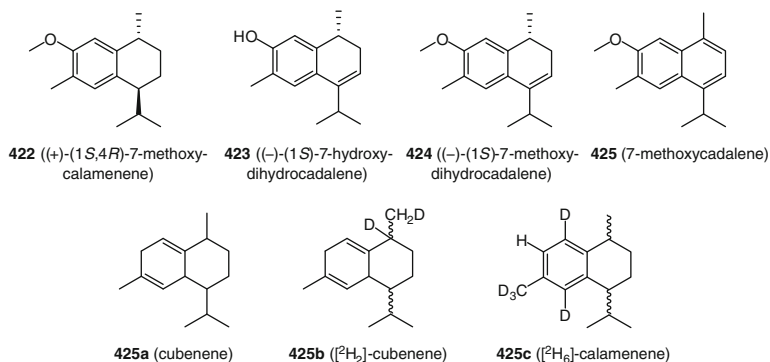
Calamenane-type and related sesquiterpenoids found in the Marchantiophyta

Compound **411** was also isolated from *H. coalitus* together with 7-hydroxycalamenene (**408**) and 7-hydroxy-8-acetoxycalamenene (**413**) ([864](#)). The ethanol extract of the Chinese *Chiloscyphus polyanthus* was purified by CC to give two rearranged calamenenes named chiloscyphephenols A (**414**) and B (**415**) as well as the *seco*-type compound, chiloscyphephenol A (**416**). A similar compound, bazzaniol A (**417**), was also isolated from *Bazzania japonica*. Detailed analysis of their HMBC spectra suggested that compounds **414**, **415**, and **417** are all calamenene-type sesquiterpenoids with a rearranged methyl group at C-7. The structures of **414**,

415, and **417** were deduced from their NOESY spectroscopic data and from analogous information for the monoacetate of **414**, but without their absolute configurations being obtained. The structure of bazzaniol A was proposed as **417** by DEPT and NOESY NMR analysis. This is the first record of the isolation of rearranged calamenenes from liverworts (**498**).

A trinosesquiterpene, tetrahydronaphthalenone-4 (= 1,6-dimethyltetrahydronaphthalen-4-one) (**418**), was isolated as a racemate from the Japanese *Jungermannia truncata* (**569**). The same compound has been obtained from *Siparuna macrotepala* (Monimiaceae) (**205**). Two *Bazzania* species and *Calypogeia muelleriana* elaborate α - (**419**) and γ -calacorene (**420**), and cadalene (**421**), as shown in Table 4.2.

Nabeta and associates reported the presence of the four calamenenes, **409**, **422**, **424**, and **425**, from *in vitro*-cultured *H. planus* (**560**). Compounds **422**, **424**, and **425** have not yet been isolated from field-collected *H. planus*. Further investigation of the cultured cells of *Heteroscyphus planus* led to the isolation of 7-hydroxycalamenene (**409**), 7-methoxycalamenene (**422**), 7-hydroxydihydrocadalene (**423**), 7-methoxydihydrocadalene (**424**), and 7-methoxycadalene (**425**). The formation of 7-hydroxycalamenene (**409**) may be the first step in the biosynthesis of hydroxylated derivatives, but the modes of aromatization and introduction of the hydroxy group to the aromatic ring still remain to be established. Direct evidence for the conversion of exogenously supplied cubenene (**425a**), but not calamenene (**403**), to 7-hydroxycalamenene (**409**), which is the precursor for the formation of compounds **422–425** in suspension cultured cells of *H. planus*, was provided by administration of [$^2\text{H}_2$]cubenene (**425b**) and [$^2\text{H}_6$]calamenene (**425c**) (**303**).



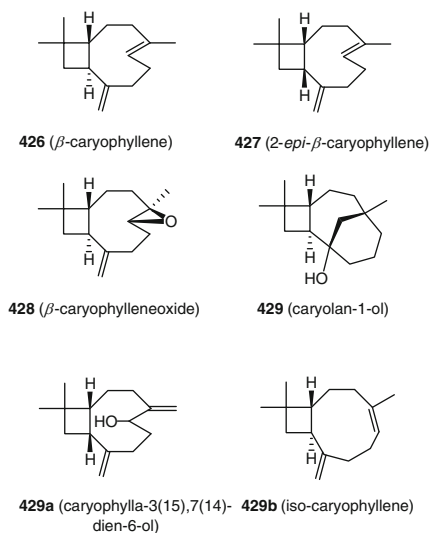
Calamenane-type sesquiterpenoids found in the Marchantiophyta and their deuterated derivatives

4.2.15 *Caryophyllanes*

β -Caryophyllene (**426**) and β -caryophyllene oxide (**428**) are very common sesquiterpene hydrocarbons among the liverworts. In Table 4.2, it is shown that compound **426** has been identified in 33 species of both the Jungermanniales and Marchantiales. Generally, their (–)-enantiomers are predominant, but some species produce both enantiomers, and, in very rare cases, the (+)-enantiomers are present with a 100% *ee*, as mentioned below.

Using a GC capillary column containing heptakis(2,6-di-*O*-methyl-3-*O*-pentyl)- β -cyclodextrin, both (+)- and (–)- β -caryophyllene (**426**) were detected in *Pellia epiphylla* (20.21: 79.79; 11.29: 88.71%), *Pellia endiviifolia* (39.70:60.30; 85.61:14.39%), and *Metzgeria conjugata* (10.86: 89.14%). *Trichoclea tomentella*, *Ptilidium pulcherrimum*, *Fossombronina alaskana* *F. pusilla* were also analyzed, but they were found to produce (–)- β -caryophyllene (**426**) (**230**).

β -Caryophyllene (**426**) and β -caryophyllene epoxide (**428**) were isolated from the German *Preissia quadrata*. Both compounds occurred as unusual (+)-enantiomers in 100% *ee* (**433**). *Dumortiera hirsuta* was hydrodistilled to obtain an essential oil, which was analyzed by capillary gas chromatography with a cyclodextrin stationary phase to identify β -caryophyllene (**426**), of enantio-excess 95:5 for the (+)- and (–)-enantiomers (**707**). β -Caryophyllene (**426**) isolated from *Bazzania japonica* also possesses the unusual (+)-enantiomeric form (**485**).



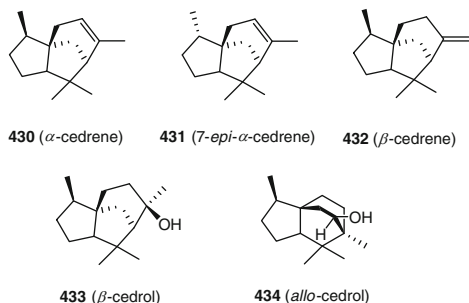
Caryophyllane-type sesquiterpenoids found in the Marchantiophyta

The Pakistani *Plagiochasma appendiculatum* produces (–)- β -caryophyllene (**426**) and its epoxide **428**. The latter compound was shown to be an autooxidized artifact, which was formed during the long storage of its extract of origin (**861**). 2-*epi*- β -Caryophyllene (**427**) was found in *Marsupella emarginata* (**17**). The GC/MS analysis of an ether extract of *Marchantia paleacea* confirmed the presence of caryophylla-3(15),7(14)-dien-6-ol (**429a**) (**424**).

4.2.16 Cedranes

The presence of cedranes is relatively rare among the liverworts. α - and β -Cedrenes (**430**, **432**), 7-*epi*-cedrene (**431**), and β -cedrol (**433**) have been found in this group of lower plants, and, among these, compound **430** is the predominant component. *allo*-Cedrol (**434**), which is a rare tricyclic sesquiterpene found in the higher plant,

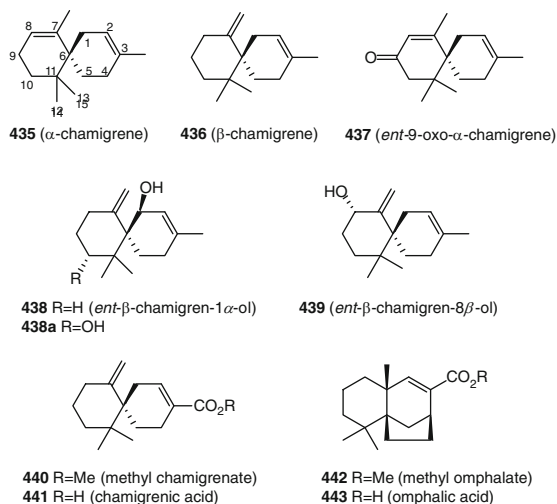
Juniperus rigida (835), was isolated from the ether extract of the North American *Porella navicularis* (143).



Cedrane-type sesquiterpenoids found in the Marchantiophyta

4.2.17 Chamigranes

α - (435) and β -Chamigranes (436) are found in nine and sixteen liverwort species, respectively (Table 4.2). The (+)-isomer of compound 435 was isolated from *Scapania undulata* (16). Ludwiczuk and colleagues confirmed the presence of *ent*-9-oxo- α -chamigrene (= laurencenone C) (437) in *Marchantia polymorpha* (Fig. 4.6) (492). *Reboulia hemisphaerica* produces not only aristolanes and cyclomyrtaylanes but also gymnomitrans and β -chamigrane sesquiterpenoids. Further fractionation of the Japanese *R. hemisphaerica* resulted in the isolation of two new compounds, *ent*- β -chamigren-1 α -ol (438) and *ent*- β -chamigren-8 β -ol (439), with their presence confirmed by Ludwiczuk and associates (492). The structure and absolute configuration of compound 438 was established by a combination of X-ray crystallographic analysis of its 3,5-dinitrobenzoate prepared from 438 and the modified Mosher method on the metabolite (438a) prepared from 438 by the fungus *Aspergillus niger* (242).



Chamigrane- and omphalane-type sesquiterpenoids found in the Marchantiophyta



Fig. 4.6 *Marchantia polymorpha*

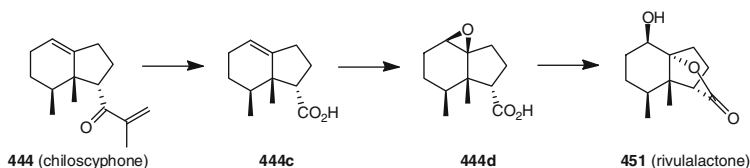
The isolation and the structure of *ent*- β -chamigrene (**436**) and methyl *ent*- β -chamigrenate (**440**), chamigrenic acid (**441**), methyl omphalate (**442**), and omphalic acid (**443**) from the Colombian liverwort, *Omphalanthus filiformis* have been reported, and their biogenesis pathway proposed in a preliminary manner (**40**). The elucidation of their stereostructures, inclusive COSY, TOCSY, HMBC, and NOESY NMR examination, has been published by *Tori* and associates (**844**).

4.2.18 *Chiloscyphanes and Oppositanes*

The ether extract of *Chiloscyphus polyanthos* was fractionated on silica gel and Sephadex LH-20 to give (–)-chiloscyphone (**444**) and (+)-chiloscypholone (**445**) (**890**). The total syntheses of chiloscyphone (**444**) and isochiloscyphone (**444a**) were accomplished by *Shiina* and *Nishiyama* using the tricyclic keto lactone **444b**, which was obtained from an intramolecular *Diels-Alder* reaction (**741**).

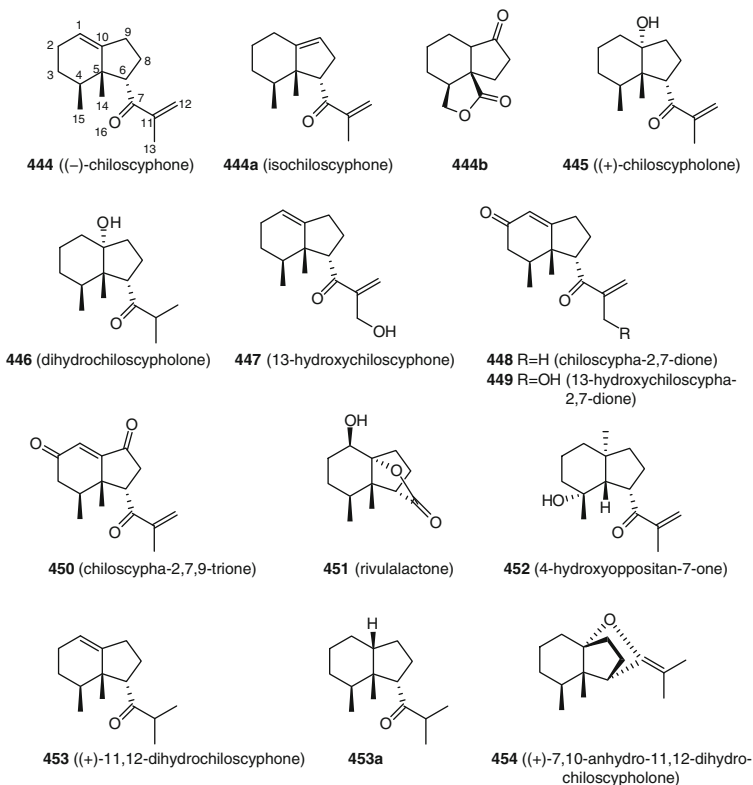
Purification of the ether extract of *Jungermannia vulcanicola* on Sephadex-20 gave a new chiloscyphane sesquiterpene ketone, dihydrochiloscypholone (**446**), along with chiloscypholone (**445**), which was isolated from *Chiloscyphus polyanthos* and with its absolute structure established by X-ray crystallographic analysis of its camphanic ester (**40**). The new compound was assigned as the dihydro derivative of **445** since catalytic hydrogenation gave a dihydro derivative with identical spectroscopic data to those of the natural product **446** (**585**).

Bioassay-directed fractionation of the methyl ethyl ketone extract of *Chiloscyphus rivularis* gave five new chiloscyphane sesquiterpenoids, 13-hydroxychiloscyphone (**447**), chiloscypha-2,7-dione (**448**), 13-hydroxychiloscypha-2,7-dione (**449**), chiloscypha-2,7,9-trione (**450**), and rivulalactone (**451**), along with the known



Scheme 4.6 Formation of rivulalactone from chiloscypnone

chiloscypnone (**444**), 4-hydroxyoppositan-7-one (**452**), and the eudesmane, isointermedeol (**608**). The structure of **447** was assigned as the 13-hydroxy derivative of chiloscypnone (**444**) by COSY, HETCOR, HMBC, and NOESY NMR data interpretation. The absolute configuration of **447** was proven by its negative *Cotton* effect at 348 nm. The structures of **448**, **449**, and **450** were assigned as 2-oxochiloscypnone, 2-oxo-12-hydroxychiloscypnone, and 2,9-dioxychiloscypnone using the same methodology as mentioned above. The structure of the trinorsesquiterpene, rivulalactone (**451**), was deduced using 2D-NMR spectroscopic measurements. Conclusive evidence of the structure was obtained by the partial synthesis of **451**. Treatment of chiloscypnone (**444**) with OsO_4 in acetone gave the 11,12-diol, followed by oxidation with *m*-chloroperbenzoic acid to afford compound **451**. This new trinorsesquiterpene lactone might originate from chiloscypnone (**444**), *via* a side chain degradation, followed by epoxidation and intramolecular cyclization, as shown in Scheme 4.6 (956).

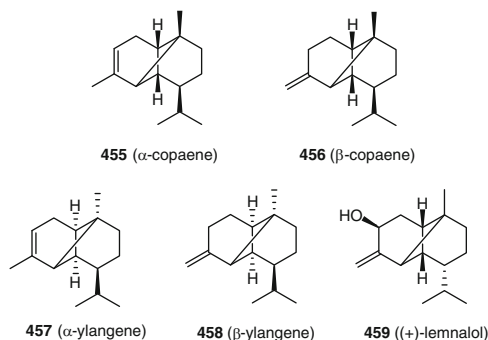


Chiloscypnone- and oppositane-type sesquiterpenoids found in the Marchantiophyta

From the essential oils of the Taiwanese *Lepidozia fauriana*, the three chiloscyphanes **446**, **453**, and **454** were isolated by preparative GC. 2D-NMR experiments (COSY, HMBC, NOE) aided in the structural determination of **454** as (+)-7,10-anhydro-11,12-dihydrochioscypholone. Further evidence for the structure of **454** was obtained from the chemical relationships between this chiloscyphane and compounds **446** and **453**. Acidic treatment of **446** with Amberlyst® resin gave **454**, which was further converted to **453**. Hydrogenation of **446**, **453**, and **454** produced the common dihydro derivative of (+)-11,12-dihydrochiloscyphone (**453**), namely, compound **453a**. Compounds **453** and **454** might be artifacts generated from **446** because of its instability (**645**). The presence of compound **453** in *L. fauriana* collected in Borneo was confirmed recently (**490**).

4.2.19 Copaanes and Ylanganes

α -Copaene (**455**) is distributed mainly in *Frullania* and *Plagiochila* as shown in Table 4.2. The presence of (+)- α -copaene (**455**) in the essential oil of *Preissia quadrata* was confirmed by capillary GC on octakis(6-*O*-methyl-2,3-di-*O*-pentyl)- γ -cyclodextrin (**433**). *Dumortiera hirsuta* was also treated in the same manner as described above to identify α -copaene (**455**) and β -copaene (**456**). The former compound showed 100% of the (+)-enantiomer and the latter substance was present as 73% of the (+)-enantiomer and 27% of the (–)-enantiomer (**707**).



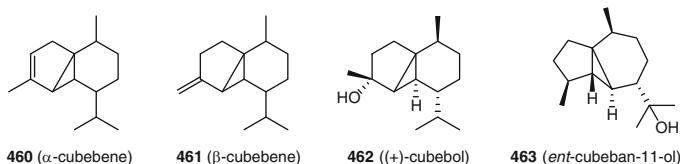
Copaane- and ylangane-type sesquiterpenoids found in the Marchantiophyta

The sterile and the male thalli of *Monoclea forsteri* elaborated not only bis-benzyls and unsaturated fatty acids (**40**) but also α -copaene (**455**) (**72**). *Lepidozia*, *Scapania*, and *Marsupella* species elaborates α - (**457**), β -ylangenes (**458**), and/or lemnalol (**459**) (**16**, **17**, **645**).

4.2.20 Cubebanes

Dumortiera hirsuta was hydrodistilled to obtain an essential oil, which was analyzed by a capillary GC method with a cyclodextrin phase to identify α -cubebene (**460**), for which the (–)- and (+)-enantiomeric ratio was 25:75% (**707**). Application of the HS-

SPME (head space-solid phase microextraction) technique coupled with GC/MS analysis led to detection of volatile components of *Drepanolejeunea madagascariensis*, including the presence of α -cubebene (**460**) (247). The ether extract of *Bazzania spiralis* collected in Borneo and of an unidentified *Pallavicinia* species were investigated by GC/MS to identify α -cubebene (**460**) and cubebol (**462**), respectively (490). β -Cubebene (**461**) was found in the German *Pellia endiviifolia* and *Symphogyna brasiliensis* from Ecuador (492).



Cubebene-type sesquiterpenoids found in the Marchantiophyta

From the essential oil of *Preissia quadrata*, (+)-cubebol (= cubebanol) (**462**), with an *ee* of 100%, was isolated by preparative GC (433). Thiel and Adam studied the biosynthesis of cubebol (**462**) using [1- ^{13} C]1-deoxy-D-xylose and suggested that this sesquiterpene is formed in the cytoplasm of the green cells of *Conocephalum conicum* (831).

The physical and spectroscopic data of cubeban-11-ol (**463**) isolated from *Jackiella javanica* were identical to those of (+)-cubeban-11-ol (940) except for the sign of the optical rotation. Thus, compound **463** is *ent*-cubeban-11-ol (608).

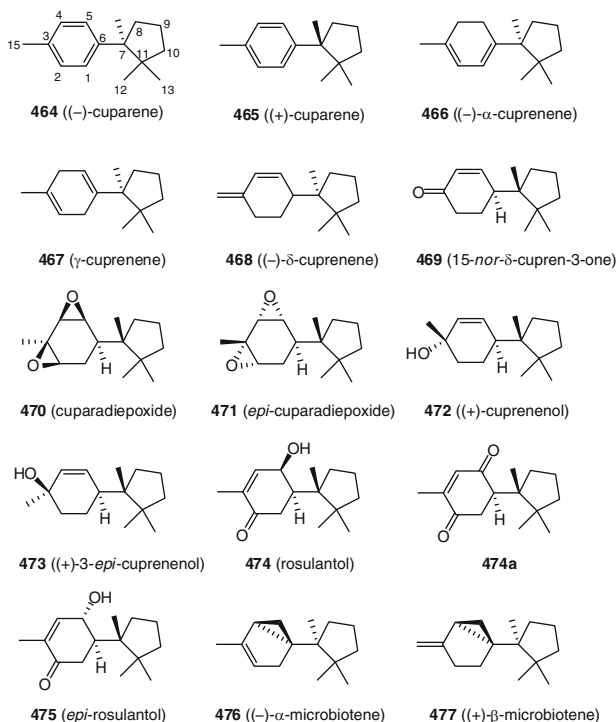
4.2.21 Cuparanes and Herbertanes

Cuparanes (**464**) are distributed widely not only in the Jungermanniales but also the Marchantiales, as shown in Table 4.2, and as described previously (40). (–)-Cuparene (**464**) was isolated only from *Lepidozia* (681), *Mannia* species (542), and *Marchantia berteriana* (72). The (+)-enantiomer (**465**) was obtained from two *Jungermannia* species (590, 599). Other widespread cuparanes are 2-cuparenol (**483**), including the (–)-enantiomer, and (–)- δ -cuprenene (**468**). In addition, α -cuprenene (**466**) and γ -cuprenene (**467**) are also distributed quite commonly in many liverwort species.

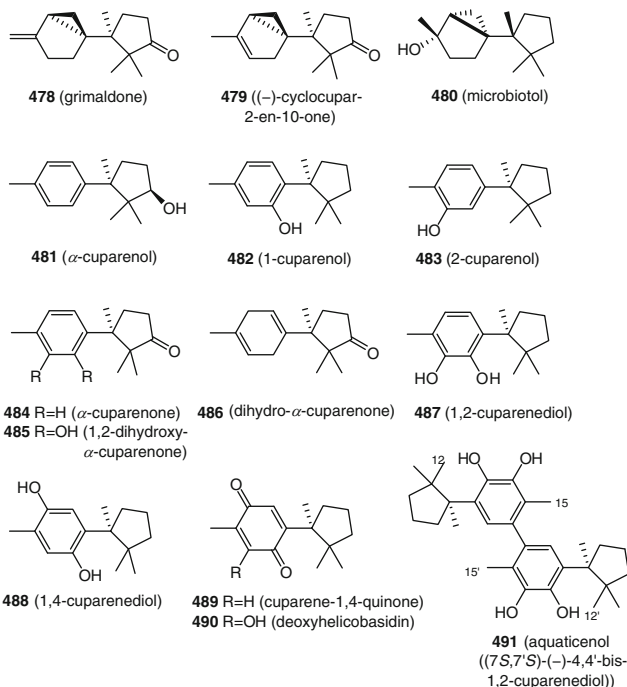
The hydrodistilled oil of the Taiwanese *Bazzania tridens* was purified by CC to give a norcuparenone (**469**), for which the gross structure was assigned as 15-*nor*- δ -cupren-4-one (**469**) by 2D-NMR spectroscopic methods (959). Cuparadiepoxide (**470**) and *epi*-cuparadiepoxide (**471**), isolated from *Jungermannia hattoriana*, have the same molecular formula and their NMR spectra were found to closely resemble one another. Both structures were solved by X-ray crystallographic analysis. The absolute configuration of **470** was clarified by the modified Mosher's method to be (1*S*,2*S*,3*R*,4*R*,6*R*,7*S*)-diepoxycuparane. In turn, compound **471** was solved as (1*R*,2*R*,3*S*,4*S*,6*R*,7*S*)-diepoxycuparane, the epimer of **470**. *J. hattoriana* also elaborates (+)-cuprenenol (**472**) and (+)-3-*epi*-cuprenenol (**473**), possessing the same molecular weight. The structure of the former compound was proven by X-ray crystallographic analysis of the C-1/C-2 mono epoxide prepared from **472**. The stereostructure of the known

rosulantol (**474**) was further determined by means of X-ray crystallographic analysis. The spectroscopic data of (+)-3-*epi*-cuprenenol (**473**) were identical to those of neocuprenenol (**473**) obtained earlier from the same plant but without a determination of its absolute configuration (**590**). In order to determine the absolute configuration of **473**, oxidation of this compound by AD-mix α was carried out to afford a triol for which the relative stereochemistry was determined by analysis of 2D-NMR spectroscopic and X-ray crystallographic data. Thus, the structure of **473** was determined as (+)-3-*epi*-cuprenenol (**473**) (**600**), a compound already reported as a reaction product (**525**). The co-occurrence of acorane diepoxide and cuparane diepoxide in the same liverwort represents the first such observation from a liverwort (**590**).

The essential oil of *Mannia fragrans* was analyzed by enantioselective GC with a modified cyclodextrin as stationary phase to identify (–)-cuparene (**464**), (–)- α -cuprenene (**466**), (–)- γ -cuprenene (**467**), (–)- δ -cuprenene (**468**), and grimaldone (**478**). (–)- α -Microbiotene (**476**) and (+)- β -microbiotene (**477**) as well as (–)-cyclocupar-2-en-10-one (**479**) were isolated from this essential oil by preparative GC and their structures elucidated by the use of 1- and 2D- NMR spectroscopic techniques. The absolute configuration of (–)-microbiotol (**480**), when isolated from a higher plant, *Microbiota decussata*, was established also by Tkachev and coworkers (**833**). This compound was dehydrated by POCl₃ in pyridine affording several hydrocarbons, among which two were identical to α -microbiotene (**476**) and β -microbiotene (**477**). However, their signs of optical rotation were opposite to those of α - (**476**) and β -microbiotene (**477**) isolated from *M. fragrans*. Thus, the absolute configurations of the liverwort microbietenes **476** and **477** were established (**542**).



(–)-Grimaldone (**478**) emits a strong mossy odor. The first total synthesis of racemic grimaldone (**478**) was accomplished by *Srikrishna* and *Ramachary* employing an acid-catalyzed rearrangement of a diazo ketone and an intramolecular cyclopropanation of a diazo ketone as a key reaction, starting from *Hagemann's* ester, *rac*-ethyl 2-methyl-5-oxocyclohex-3-ene carboxylate. Racemic α -cuparenone (**484**) was also synthesized through this protocol (**775**). α -Cuparenol (**481**) was also detected in *Lepidozia concinna* (**72**).



Cuparane-type sesquiterpenoids found in the Marchantiophyta

The New Zealand *Riccardia eriocaula* was found to elaborate 2-cuparenol (**483**) as a predominant constituent along with 1,2-dihydroxy- α -cuparenone (**485**) (**72**). Fractionation of the ether extract of the New Zealand *Lunularia cruciata* led to the isolation of 2-cuparenol (**483**) and lunularin (**1477**) as the major constituents. Cuparene (**464**) has also been detected by GC/MS of the crude extract of the species. The Japanese *L. cruciata* has been shown to elaborate the bisbibenzyls, perrottetin F (**1639**) and 7',8'-dehydroperrottetin F (**1641**), as well as a bis-bibenzyl dimer, cruciatin (**1659a**) (**40**). However, these types of bibenzyls were not found in a New Zealand specimen of the same species (**72**).

The New Zealand *Symphyogyna prolifera* and *S. podophylla* are chemically similar since both liverworts elaborate α -cuparenone (**484**) as the major component. The latter species also produces drimenol (**538**). While *S. brasiliensis* and *S. brongniartii* have been chemically analyzed, neither cuparane nor drimane sesquiterpenoids were found (**72**). α -Cuparenone (**484**) was synthesized by *Srikrishna* and *Rao* by a combination of a *Claisen* rearrangement and ring-closing methathesis reaction using



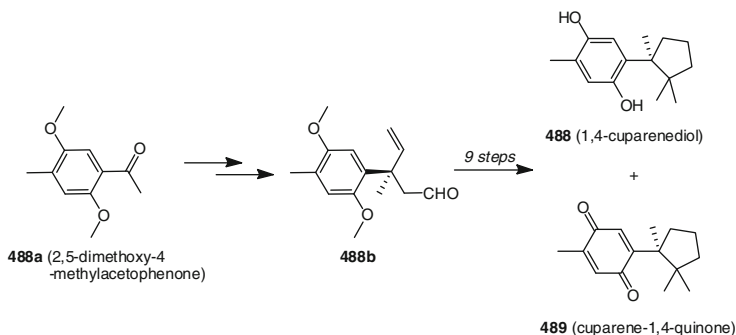
Fig. 4.7 *Radula perrottetii*

4-methylacetophenone as the starting material (776). The total synthesis of racemic α -cuparenone (484) has been achieved using α,α -dimethylation of methyl 3-methyl-3-*p*-tolyl-6,6-ethylenedioxyhexanoate as the key step (647).

The GC/MS analysis of the crude extract of *Lepidozia concinna* (72) and *Lejeunea aquatica* showed the presence of 1,3-dihydroxy- α -cuparenone (486) and 1,2-cuparenediol (487) as the major components. Two new cuparane sesquiterpene dimers named aquaticenol (491) and 1,4-cuparenediol (488), along with 1-cuparenol (482), 2-cuparenol (483) cuparene-1,4-quinone (489) (40), and deoxyhelico basidin (490) (618), were isolated from the crude extract of *L. aquatica*. The ether extract of *L. flava* also contained 1,2-cuparenediol (487) and cuparene-1,4-quinone (489). *L. japonica* elaborated the cuparenediols 487 and 488 and (–)-(S)-cuparene (464). The absolute configuration of 1,2-cuparenediol (487), isolated from the liverwort, *Radula perrottetii* (Fig. 4.7) (40), had not yet been determined. In order to confirm the absolute configuration of this compound, (–)-(S)-cuparene (464) isolated from *Marchantia polymorpha* and 487 were ozonized to give camphanic acid, for which the specific rotations were -12.8 from 464 and $-12.0^\circ\text{cm}^2\text{g}^{-1}10^{-1}$ from 487. Thus, the absolute configuration of 487 was established as (–)-(S)-1,2-cuparenediol. The structure of 491 was assigned by HRMS and comparison of its other spectroscopic data with those of 487. In addition, temperature-dependent ^1H NMR spectroscopy was applied, in which it was found that all of the signals appeared as pairs, particularly as a 3:2 ratio for four methyl signals. When the ^1H NMR spectrum was measured in $\text{DMSO}-d_6$ at 130°C , the paired signals at δ_{H} 0.72/0.74 ppm assignable to H-12 or H-12' and δ_{H} 1.83/1.84 ppm to H-15 or H-15' disappeared, and the equivalent singlet signals were observed. Clearly, a conformational equilibrium between a major form and a minor form of compound 491 exists, in the ratio 3:2. A combination of X-ray crystallographic analysis and 2D-NMR (HMOC and HMBC) data interpretation

showed the presence of a C-4/C-4' linkage in the molecule of **487**. For conclusive evidence of a dimeric structure including the absolute configuration, the partial synthesis of **491** was carried out. Compound **487** was treated with aluminum chloride in nitromethane, and with DDQ it afforded **491** for which the optical rotation and spectroscopic data were in good agreement with those found for the natural product. Thus, the structure and absolute configuration of aquaticenol were determined as (–)-(7*S*,7'*S*)-4,4'-bis-1,2-cuparenediol. The isomeric ratio of (*S*)-(–)- and (+)-(*R*)-aquaticenol in structure of **491** was confirmed by measurement of its CD spectrum, which showed a positive and negative *Cotton* effect at 235 nm and 270 nm, respectively, indicating that an excess of (–)-(*S*)-aquaticenol existed in a mixture. When compound **488** was allowed to stand at room temperature, it was easily converted to a quinone for which the spectroscopic data were identical to those of cuparene-1,4-quinone (**489**). Thus, the structure of **488** was assigned as 1,4-cuparenediol (**878**). The occurrence of dimeric sesquiterpenoids in liverworts is very rare (**878**). Only eudesmane-, aromadendrane-, and herbertane-type dimers have been found in *Frullania* (**40**, **443**, **886**), *Mylia*, *Plagiochila*, and *Mastigophora* (**40**).

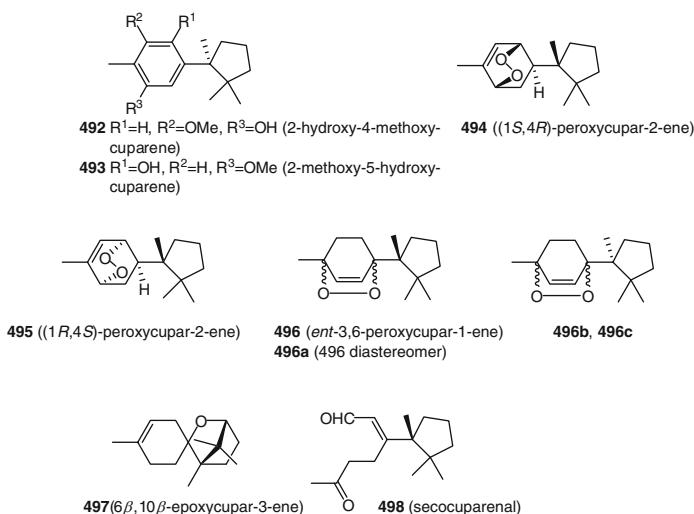
The total synthesis of cuparene-1,4-diol (**488**), isolated from *Lejeunea aquatica* (**878**), and cuparene-1,4-quinone (**489**), from *L. flava* (**878**) and *Radula javanica* (**67**), were accomplished by Srikrishna and Rao using the *Horner-Wadsworth-Emmons* reaction of 2,5-dimethoxy-4-methylacetophenone (**488a**), followed by *Claisen* rearrangement to give **488b**, a key synthetic intermediate for both compounds. Compound **488b** was treated in a further nine steps to furnish compounds **488** and **489**, as shown in Scheme 4.7 (**777**).



Scheme 4.7 Total synthesis of cuparenediol and cuparenequinone

The Madagascan *Bazzania decrescens* elaborates 2-hydroxy-4-methoxycuparene (**492**), together with 2-methoxy-5-hydroxycuparene (**493**) and cuparene, and other common sesquiterpenoids (**291**). The ether extract of *Jungermannia infusca* collected in Tochigi, Japan, was fractionated by CC to give two new peroxy cuparenes, (1*R**,4*R**)-peroxycupar-2-ene (= (1*S*,4*R*)-peroxycupar-2-ene) (**494**) and (1*S**,4*S**)-peroxycupar-2-ene (= (1*R*,4*S*)-peroxycupar-2-ene) (**495**), together with (+)-cuprenenol (**472**) and rosulantol (**474**) (**40**). The structure and relative configuration of **494** were established by COSY, HMBC, and NOE NMR experiments and by X-ray crystallographic analysis. The epimer (**495**) of **494** was also deduced structurally

from its 2D-NMR spectra in a similar manner (591). In order to determine the absolute configuration of both compounds, rosulantol (474), of established absolute configuration, was oxidized with pyridinium dichromate (PDC) to give the diketone 474a, which was identical with a compound obtained from 494 by samarium diiodide and PDC oxidation, indicating that the absolute configurations at C-6 and C-7 of 474a are (*R*) and (*S*). Thus, the absolute stereostructures of both 496 and 495 were proven to be (1*S*,4*R*)-peroxycupar-2-ene and (1*R*,4*S*)-peroxycupar-2-ene (595). Further fractionation of the ether extract of *J. infusca* resulted in the isolation of the three new cuparene sesquiterpenoids, 475, 496, and 496a together with cuparadiepoxide (470), *epi*-cuparadiepoxide (471) (587), (+)-cuprenenol (472), and rosulantol (474) (40). The analysis of its 2D-NMR data, especially the NOESY spectrum, suggested that compound 475 is the C-1 epimer of rosulantol (474). This assumption was confirmed by the preparation of 474a from 475 by PDC oxidation and X-ray crystallographic analysis of 475. The spectroscopic data of 496 and 496a were identical to those of 3,6-peoxycupar-1-ene (496b, 496c) isolated from the liverwort *Nardia scalaris* (40), but the sign of optical rotation was opposite. Thus, the structures of both 496 and 496a were proved to be *ent*-3,6-peoxycupar-1-ene and its diastereoisomer (595).



Cuparene-type sesquiterpenoids found in the Marchantiophyta

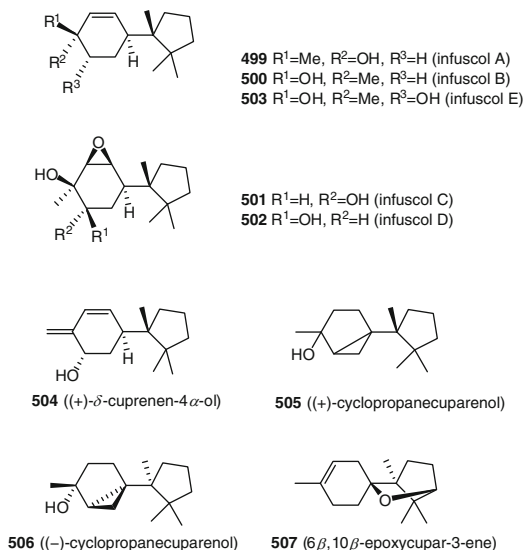
The ether extract of *Reboulia hemisphaerica* was found to contain a new cuparene sesquiterpenoid, 6 β ,10 β -epoxycupar-3-ene (497), and the known (–)-cyclopropanecuparenol (506) (40). The positioning of the ether substituent and the relative configuration of 497 were based on its HMQC, HMBC, and NOESY NMR spectroscopic assignments (889). Further investigation of this same liverwort collected in a different location led to the isolation of cyclopropanecuparenol (506) and 6 β ,10 β -epoxycupar-3-ene (507) (436). The ether extract of the Japanese *Marchantia polymorpha* was reinvestigated by GC/MS. It was found to elaborate mainly cyclopropanecuparenol (506), a compound isolated previously from the same species (492).

The $CDCl_3$ extract of *Cryptothallus mirabilis* showed the presence of (2*S*,6*S*)-cyclo-(7*S*)-cuparan-(3*S*)-ol (= (–)-cyclopropanecuparenol (506)) for which the absolute

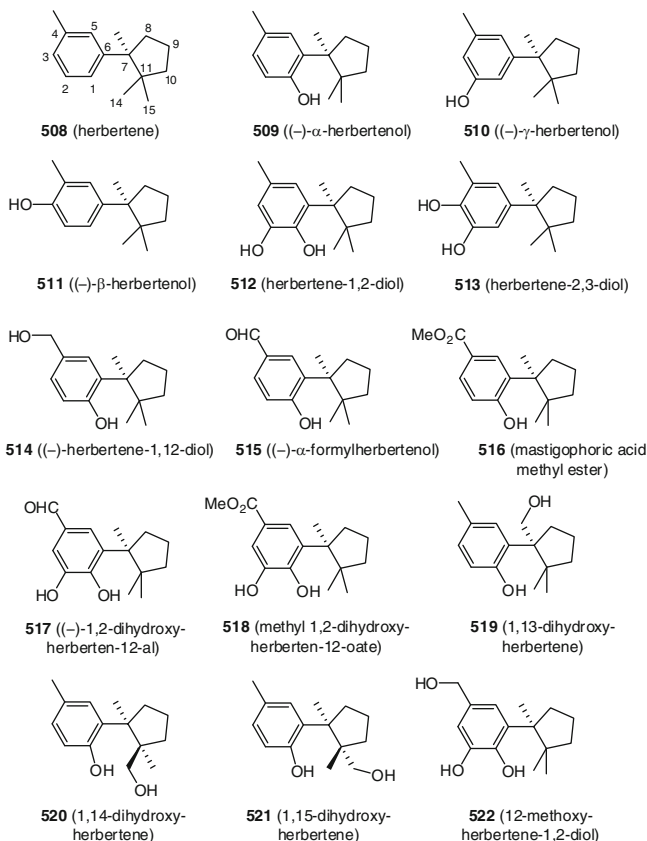
configuration was assumed from the formation of *ent*-cuparene (**464**) and by comparison of its spectroscopic data with those of grimaldone (**478**) from *Mannia fragrans*. A comparison of the ^1H NMR spectrum of **506** was made with that of (–)-cyclopropanecuparenol isolated from *Marchantia polymorpha*, for which the relative configuration was assigned as (7*S*,6*R*,2*R*,3*R*) by NOE experiments. The procedure described above demonstrated clearly that both compounds are the same. This represents the first isolation of cyclocuparene from a liverwort in the order Metzgeriales (**692**).

Jungermannia infusca elaborates a *seco*-sesquiterpene aldehyde, secocuparenal (**498**), with its structure and relative configuration elucidated by 2D-NMR experiments (**599**). Racemic secocuparenal (**498**) was synthesized by Srikrishna *et al.* using the abundantly available β -ionone (**781**).

Further fractionation of the ether extract of *Jungermannia infusca* led to the isolation of seven new cuparenoids, infuscols A-E (**499–503**), δ -cuprenen-4 α -ol (**504**), and cyclopropanecuparenol (**505**). The structures of compounds **499** and **500** were clarified as 3 α -hydroxycupar-1-ene and 3 β -hydroxycupar-1-ene by X-ray crystallographic analysis of the epoxide of **499** by *m*CPBA. The X-ray crystallographic analysis of **501** showed that its structure is 1 β ,2 β -epoxycupara-3 β ,4 α -diol. In turn, the structures of infuscols D (**502**), E (**503**), and compound **504** were confirmed as 1 β ,2 β -epoxycupara-3 β ,4 β -diol, 3 β ,4 α -dihydroxy-1-cuparene, and (+)- δ -cuprenen-4 α -ol, based on 2D-NMR data interpretation and comparison with analogous values of previously isolated cuparenes. The physical and spectroscopic data of **505** were identical to those of (–)-cyclopropanecuparenol (**506**) isolated from *Marchantia polymorpha* (**40**) and *Reboulia hemisphaerica* (**436**), except for the positive sign of the optical rotation. Thus, **505** was assigned as (+)-cyclopropanecuparenol. The configuration of the cyclopropane ring remains to be clarified, however (**600**). *R. hemisphaerica* produces 6 β ,10 β -epoxycupar-2-ene (**507**), for which the relative configuration was elucidated using its 2D-NMR spectroscopic data (**436**).



Previously, eleven herbertanes have been found in only a limited number of liverworts, embracing three *Herbertus*, two *Mastigophora* (morphologically primitive), two *Plagiochila*, a *Triandrophyllum* and a *Marchantia* species (40). As seen in Table 4.2, herbertene (508) and α -herbertenol (509) are the most frequently identified herbertenoids in liverworts.



Herbertane-type sesquiterpenoids found in the Marchantiophyta

GC/MS analysis of *Wettsteinia schusterana* indicated the presence of herbertene (508) and α -herbertenol (509). This represents the first detection of herbertane sesquiterpenoids, the most important chemical markers of the Herbertaceae, in the Adelantaceae. *W. schusterana* was found to produce β -barbatene (235), bicycloelemene (290), bicyclogermacrene (293), β -bisabolene (315), α -humulene (767), and fusicoccadiene (1095) (70).

The ether extract of the New Zealand *Bazzania novae-zelandiae* contained α -herbertenol (509) (615). Fractionation of the ether extract of the New Zealand *Dendromastigophora flagellifera* led to the isolation of the known herbertane sesquiterpenoids, herbertene (508), α -herbertenol (509), γ -herbertenol (510), β -herbertenol (511), herbertene-1,12-diol (514), herbertenone A (525), and herbertenone B (526), and, among these, compounds 525 and 526 were the major

components. The last two compounds have been isolated from the Japanese *Herbertus sakuraii* and their absolute stereostructures assigned tentatively (365). Conclusive evidence for the structure of **526** was established from its NOESY spectroscopic data and by X-ray crystallographic analysis, in addition to its co-occurrence with other herbertanes in its liverwort of origin. The structure of **525** was also directly deduced as the C-3 epimer of **526** (84, 616, 635).

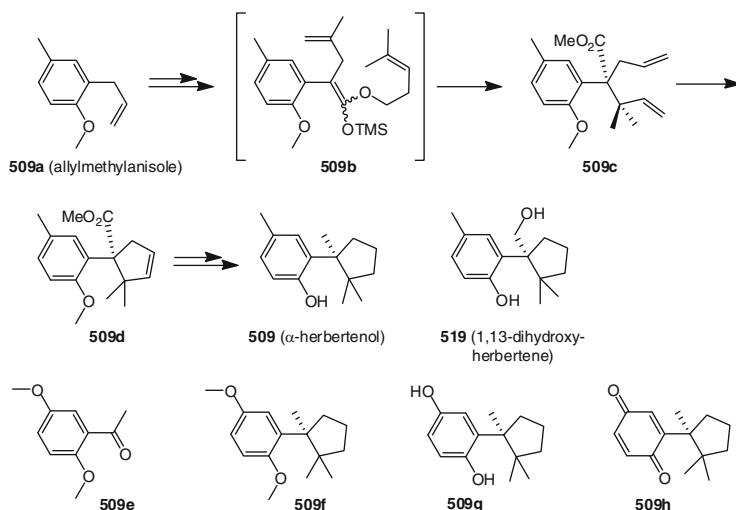
The New Zealand *Asterella australis* elaborated herbertene (**508**) along with α -herbertenol (**509**) as a minor component. This was the first identification of herbertanes in the Asterellaceae (72).

The total synthesis of (–)-herbertene (**508**) was achieved by *Tori* and associates by use of slightly modified phenylethylamine technology and a *Diels-Alder* reaction as the key step (850). The enantioselective total syntheses of (–)-herbertane (**508**) and (–)- α -herbertenol (**509**) were conducted by *Abad* and coworkers using (1*S*,2*S*)-epoxy-2,6,6-trimethylcyclohexane-1-methylcarbinol prepared from β -cyclogeraniol in seven steps, with a 28% yield. Altogether, ten steps were required for these syntheses, which resulted in 19% overall yields (2). The total synthesis of α -herbertenol (**509**) was accomplished by *Harrowven* and *Hannam* by reacting 2-methoxy-5-methylphenyl bromide with dihydropinanone (300). *Srikrishna* and *Rao* synthesized (±)-herbertene (**508**), (±)- α -herbertenol (**509**), (±)- β -herbertenol (**511**), and (±)-herbertene-1,2-diol (**512**) by a combination of a *Claisen* rearrangement and a ring closing methathesis reaction using a 4-methylacetophenone derivative as the starting material (776). *Fukuyama* and associates were able to perform the total synthesis of herbertene-1,2-diol (**512**) via herbertenol (**509**) using 1,1-dimethylcyclopent-2-en-1-carboxylic acid and 2-iodo-*p*-cresol as the starting materials, followed by an intramolecular *Heck* reaction (236). The same authors synthesized herbertene-1,2-diol (**512**) from (*R*)-1,2-dimethyl-2-cyclopentane carboxylic acid by an intramolecular *Heck* reaction. The oxidative coupling reaction of **512** using horseradish peroxidase and (*tert*-BuO)₂ afforded (–)-mastigophorenes A (**528**) and B (**529**) (240).

The formal total syntheses of racemic herbertene-1,2-diol (**512**) and racemic mastigophorenes A-D (**528–531**) were carried out by *Srikrishna* and *Rao* using vanillin as a starting material (779). In turn, the total syntheses of racemic α -herbertenol (**509**) and racemic herbertene-1,13-diol (**519**) were accomplished using an anisole derivative as the starting material, as shown in Scheme 4.8 (778).

The structure of γ -herbertenol (**510**) isolated from *Tylimanthus renifolius* (213) and *Dendromastigophora flagellifera* (635) was confirmed by its synthesis. The first total synthesis of **510** was achieved by *Srikrishna* and *Ravikumar* from the starting material, 3,5-dimethylanisole, via a combination of *Claisen* rearrangement and a ring-closing metathesis reaction (780).

The formal first total synthesis of mastigophorenes A (**528**) and B (**529**) was performed by *Bringmann* and associates (131). After transformation of herbertenediol (**512**) to a monophenolic coupling precursor, the oxidative dehydrodimerization was brought about using (*tert*-BuO)₂, followed by deprotection of the methyl from the methoxy group to furnish mastigophorenes A (**528**) and B (**529**), in 40 and 60% yields, which were nearly identical to the ratio of these natural products



Scheme 4.8 Total synthesis of racemic α -herbertenol and 1,13-dihydroxy-herbertenediol

when isolated from *Mastigophora diclados*. Bringmann and coworkers accomplished the stereoselective total synthesis of herbertene-1,2-diol (**512**) and of its naturally occurring dimers, mastigophorenes A (**528**) and B (**529**), from 3-iodo-4-hydroxy-5-methoxybenzaldehyde as the starting material. This new synthesis of herbertene-1,2-diol (**512**) established its absolute stereochemistry as well as that of its dimers ([132](#), [133](#)). Independently, the same natural products, **512**, **528**, and **529**, were synthesized using a bicyclic lactam to construct a chiral cyclopentane, and an oxazolin-mediated asymmetric *Ullmann* coupling to establish the biaryl axis of mastigophorenes A (**528**) and B (**529**) ([187](#)). Mastigophorenes C (**530**) and D (**531**) were synthesized from herbertenediol dimethyl ether as a starting material. This was the first time mastigophorenes C (**530**) and D (**531**) were synthesized ([134](#)).

Herbertenolide (**524**) was synthesized in seven steps from 2-bromo-4-methoxyanisole, which was converted to methyl-*trans*-3-(2-methyl-5-methoxyphenyl)-1,3-dimethyl-2-oxocyclohexanecarboxylate, followed by photolysis with a medium pressure mercury lamp and then treated with BBr_3 in methylene chloride to give herbertenolide in 60% yield ([776](#)). Racemic herbertenolide (**524**) was also synthesized by Ng and associates ([622](#)).

The Argentinean *Tylimanthus renifolius* contained two further new herbertanes, (–)-herbertene-1,12-diol (**514**) and (–)- γ -herbertenol (**510**), together with (–)- α -herbertenol (**509**). The structures of **510** and **514** were identified readily by comparison of their NMR spectroscopic data with those of α -herbertenol ([213](#)).

The Madagascan *Mastigophora diclados* (Fig. 4.8) produced mastigophoric acid methyl ester (**516**), together with the related herbertane sesquiterpenoids, herbertene (**508**), α -herbertenol (**509**), β -herbertenol (**511**), herbertane-1,2-diol (**512**), mastigophorene C (**530**), mastigophorene D (**531**), and α -formylherbertenol (**515**). Although compound **516** was obtained in one step in the synthesis of α -formylherbertenol (**515**), this is the first report on the isolation of **516** in Nature ([287](#)).



Fig. 4.8 *Mastigophora diclados*

Two new herbertanes, (–)-1,2-dihydroherberten-12-al (**517**) and methyl 1,2-dihydroxyherberten-12-oate (**518**), were isolated from the methanol extract of the Scottish *Herbertus aduncus* subsp. *hutchinsiae*, along with herbertene (**508**), (–)- α -herbertenol (**509**), (–)- β -herbertenol (**511**), and (–)-herbertene-1,2-diol (**512**). The structures of **517** and **518** were based on 2D-NMR spectroscopic data analysis and comparison with analogous information for herberten-1,2-diol (**512**). Herbertene (**508**) and α -herbertenol (**509**) were identified in the Scottish *H. borealis* from GC retention data and their ^1H NMR spectra ([137](#)).

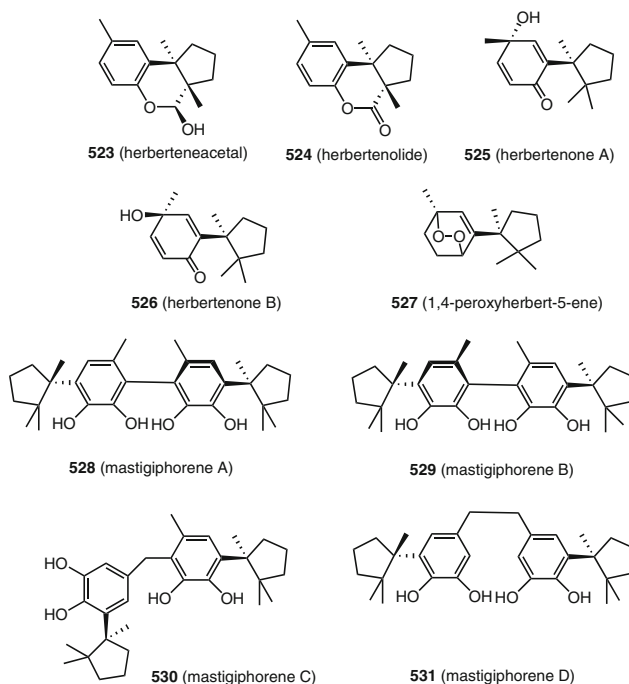
Paul and associates succeeded in a convenient and useful general method for the total synthesis of herbertane and cuparene sesquiterpenoids based on intramolecular cyclization of 3-aryl-3-methyl-6-bromohexanoates and in situ methylation of the resulting cyclopentanecarboxylates. Stereocontrolled total synthesis of racemic 1,15-herbertenediol (**521**), β -herbertenol (**511**), cuparene-1,4-diol (**488**) and cuparene-1,4-quinone (**489**) isolated from the liverworts was accomplished by the application of this method ([646](#)). Herbertenones A (**525**) and B (**526**) were isolated from *Herbertus sakuraii* along with several herbertane sesquiterpenoids ([365](#)). The first total synthesis of herbertenones was established by *Srikrishna* and associates ([782](#)). 1,4-Dimethoxy-2-(1,2,2-trimethylcyclopentyl)benzene (**509f**) (Scheme 4.8), which was obtained from 2,5-dimethoxyacetophenone (**509e**) in 12 steps, was demethylated to give the 1,4-dihydroxy derivative, **509g**, followed by oxidation with ceric ammonium nitrate in aqueous acetonitrile to afford a diketone (**509h**), which was treated with *Grignard* reagent to furnish a 2:1 mixture of herbertenones A and B (**525** and **526**) ([782](#)).

The purification of the ether extract of the New Zealand *Lepidozia setigera* gave the new herbertene peroxide (**527**), together with amorphane and aromadendranes,

as mentioned earlier. The molecular formula of **527** was assigned by CIMS. The presence of a peroxide moiety in the molecule of **527** was confirmed by the appearance of a red zone on TLC after spraying with *N,N*-dimethyl-*p*-phenylenediammonium dichloride/AcOH reagent. The complete structure for **527** was deduced as 1,4-peroxyherbert-5-ene by 1D- and 2D-NMR (HMQC and HMBC, NOESY) spectroscopy (347). This was the first isolation of a herbertane sesquiterpenoid in the genus *Lepidozia*, although cuparene sesquiterpenoids have been found in *L. borneensis*, *L. reptans*, and *L. concinna* (40). A similar ent-peroxide, 3,6-peroxocupar-1-ene (496), has been isolated from *Nardia scalaris* (40) and *Jungermannia infusca* (595, 599).

The Japanese *Herbertus sakuraii* produces not only isoplagiochin-type bis-benzyls (see Sect. 4.5.2) but also large amounts of herbertane sesquiterpenoids. GC/MS analysis of the ether and ethyl acetate crude extracts showed the presence of herbertene (508), α -herbertenol (509), and herbertene-1,2-diol (512). Further fractionation of the extracts led to the isolation of 12 compounds including seven new herbertanes, 1,13-dihydroxyherbertene (519), 1,14-dihydroxyherbetene (520), 1,15-dihydroxyherbertene (521), 12-methoxyherbertene-1,2-diol (522), herberteneacetal (523), herbertenolide (524), herbertenone A (525), herbertenone B (526), mastigophorene A (528), mastigophorene B (529), and mastigophorene C (530), of which compound 509 was the major component (15% of the total crude extract). Conclusive evidence for the structures of all of the compounds was obtained from their 2D-NMR (HMBC, HMQC, NOESY) spectra. Compounds 525 and 526 are diastereomeric at the C-4 epimeric center. Since 525 and 526 should possess the same (*S*)-configuration at C-7 as that of the known co-occurring herbertane sesquiterpenoids, herbertene (508), α -herbertenol (509) and herbertene-1,2-diol (512), 525 and 526 should have the (4*S*) and (4*R*) configuration, respectively. For the formation of 525 and 526, Hashimoto and associates suggested a radical reaction from α -herbertenol (509) with subsequent isomerization, where one electron is eliminated, and finally a hydroxy group is introduced to furnish herbertenones A (525) and B (526) (321, 323). The ether extracts of Canadian and Japanese specimens of *Herbertus aduncus* were reinvestigated by GC/MS. The former sample produced herbertane-1,2-diol (512) and herbertenolide (524), herberteneacetal (523), and the latter herbertenolide (524), 1,15-dihydroxyherbetene (521), herberteneacetal (523), herbertene (508), α -herbertenol (509), herbertene-1,2-diol (512), 1,2-dihydroxyherbertene-12-al (517), and 1,14-dihydroxyherbetene (520) (323).

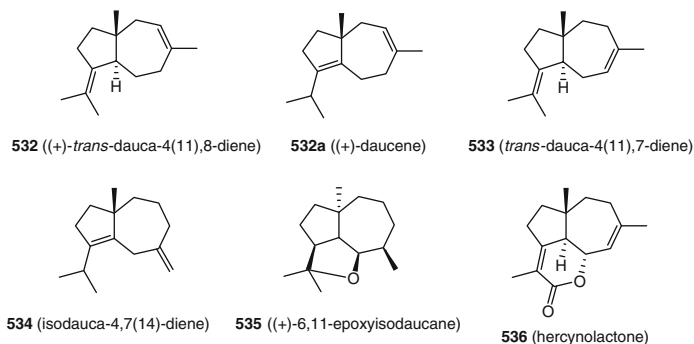
It was found that specimens of *Mastigophora diclados* collected in Madagascar and Borneo produced mainly herbertane sesquiterpenoids (40, 287). Further chemical analysis of the crude extract of Tahitian *M. diclados* by GC/MS confirmed the presence of herbertene (508) (30%), α -herbertenol (509) (15.4%), and herbertene-1,2-diol (512) (22%), together with β -herbertenol (511) as a minor component (494).



Herbertane-type sesquiterpenoids found in the Marchantiophyta

4.2.22 Daucanes

(+)-*trans*-Dauca-4(11),8-diene (**532**) was isolated from the essential oils obtained by hydrodistillation of specimens of *Bazzania trilobata* collected in Europe and North America. The relative configurations of the stereogenic centers at C-1 and C-5 were determined by a NOESY NMR experiment. Acid treatment of **532** gave *trans*-dauca-4,8-dienene (= (+)-daucene) (**532a**). The same saturated daucanes were prepared by hydrogenation of both **532** and **532a** (930). *Ludwiczuk* and colleagues identified two daucanes, *trans*-dauca-4(11),7-diene (**533**) and isodauca-4,7(14)-diene (**534**) from *Symphogyna brasiliensis* and *Radula perrottetii*, by GC/MS (492).



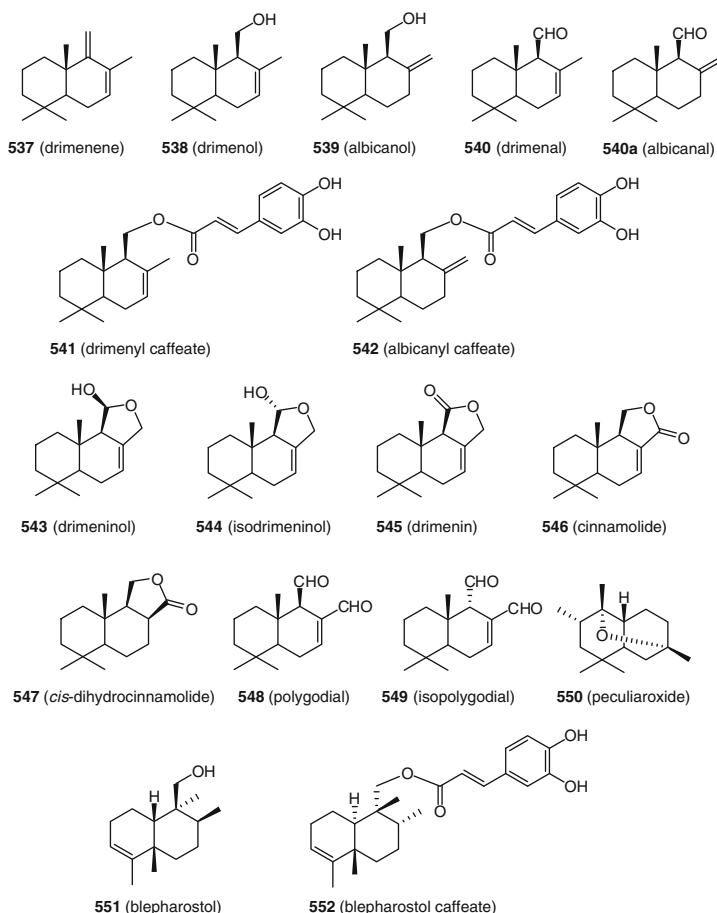
Daucane-type sesquiterpenoids found in the Marchantiophyta

The essential oil obtained by hydrodistillation of *Tritomaria polita* elaborates not only many oxygenated eudesmanes, but also (+)-6,11-epoxyisodaucane (**535**), for which the relative structure was confirmed by 2D-NMR experiments (HMBC, HMQC and NOESY) (18).

Barbilophozia lycopodioides (40), *B. barbata* (583), *B. hatcheri* (593, 596) produce the known daucane sesquiterpenoid, hercynolactone (**536**) (357).

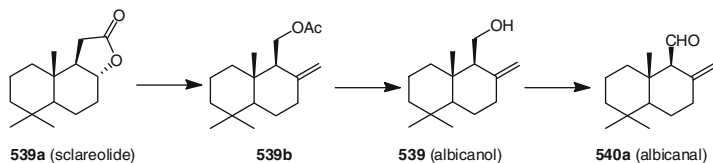
4.2.23 Drimanes

Bazzania and *Porella* species are rich sources of drimane sesquiterpenoids (39, 40). Drimenene (**537**), the simplest drimane hydrocarbon, was identified in the essential oil of *Bazzania trilobata* (930).



Drimane- and rearranged drimane-type sesquiterpenoids found in the Marchantiophyta

Drimenol (**538**) and albicanol (**539**) are distributed widely in species of the genus *Bazzania* (490, 582, 821, 951). Peculiaroxide (**550**) has been obtained from *Lepicolea ochroleuca* (478) and *Plagiochila* species (32), as shown in Table 4.2.



Scheme 4.9 Formation of drimane-type sesquiterpenoids from sclareolide

Komala and associates reported the isolation of an enantiomer, (+)-drimenol, from the Tahitian *Mastigophora diclados* (425). This is the first time for the isolation of the (+)-enantiomer as a natural product, although it has been reported as a synthetic compound (988).

Drimenal (540) was isolated from *Bazzania trilobata* together with drimenol (538) (715). Previously, the presence of 540 in the higher plant, *Drymis winteri*, was confirmed by GC/MS (104).

Albicanol (540a), the C-8(C-11) diastereomer of 540, has been isolated from the liverwort *Diplophyllum serrulatum* (40, 868). Albicanol (539) was also isolated from the Japanese *Bazzania yoshinagana* (821), the Chinese *Cephalozia recurvifolia* (955), and the American *Porella navicularis* (143). The previously known compounds, drimenyl caffeate (541) and albicanyl caffeate (542), were found in the Madagascan *Bazzania decrescens* (291) and *B. yoshinagana* (821).

Porella fauriei was reinvestigated chemically to give the known drimeninol (543), polygodial (548), and cinnamolide (546), found earlier in the same species (40), together with the newly isolated dihydroxycinnamolide (547). Albicanol (539) and albicanal (540a) were prepared from sclareolide (539a), as shown in Scheme 4.9 (661).

Porella canariensis produces pungent compounds. The ether extract of *P. canariensis* collected in Portugal was fractionated to give isodrimeninol (544), cinnamolide (546), and *cis*-dihydrocinnamolide (547). The physical and spectroscopic data of these compounds were identical to those of authentic samples. *P. canariensis* is very pungent, like *P. arboris-vitae*, which produces a large amount of polygodial (548). The pungency of the former species may be attributable to this compound. The isolation of polygodial could be not achieved from *P. arboris-vitae* by extraction with methanol (582, 604). Further fractionation of the dichloromethane extract of this plant collected in Madeira led to the purification of the known drimenol (538), drimeninol (543), drimenin (545), cinnamolide (546), and polygodial (548) (179).

Porella vernicosa (Fig. 4.9) was cultured *in vitro* in Murashige and Skoog's medium. Polygodial (548) was found as the major metabolite (20.3%), together with drimenol (538, 8.4%), cinnamolide (546, 5.5%), and isopolygodial (549), with the latter compound possibly being formed as an artifact during GC analysis (637).

Peculiaroxide (550), which was found in *Plagiochila peculiaris* (40), was also isolated from the dichloromethane extract of the South American *P. dusenii* (32). The essential oils of four Madeiran *Plagiochila* species, *P. bifaria*, *P. maderensis*, *P. retrorsa*, and *P. stricta* were analyzed by GC and GC/MS. All four species contained peculiaroxide (550), at concentration levels between 8.9% and 21.0%



Fig. 4.9 *Porella vernicosa*

(221). The same compound has been identified in the essential oil of *Plagiochila bifaria* (277, 334).

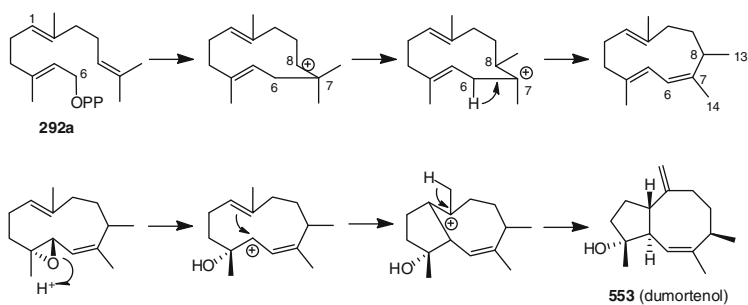
Blepharostol (551), a new rearranged drimane sesquiterpenoid or degraded clerodane diterpenoid, was isolated from a very small liverwort, *Blepharopstoma trichophyllum* (215), and its caffeate (552) was obtained from *Bazzania novae-zelandiae* (899, 901).

4.2.24 *Dumortanes*

Previous studies of the Japanese *Dumortiera hirsuta* (Fig. 4.10) showed the presence of (4*S*,6*R*-2,7,10)-bisabolatrien-4-ol (330), (4*S*,7*R*)-germacra-(1(10)*E*,5*E*)-dien-11-ol (698), (1(10)-*E*)-lepidozen-5-ol (309), the monobibenzyl lunularin (1477), and the bis-bibenzyls riccardin C (1566), marchantin C (1579), and isomarchantin C (1592) (876, 883). Frequently, when the same liverwort species is studied chemically, the constituents found are often somewhat different (40). In order to compare the constituents of the Japanese and Argentinian *Dumortiera hirsuta*, the ether extract of the latter specimen was analyzed to afford the new sesquiterpene alcohol 553, named dumortenol, based on a novel carbon skeleton, for which the gross structure was proposed by 2D-NMR (COSY, HMQC, HNMBC, and NOESY) data interpretation. Conclusive evidence for this structure was obtained from its X-ray crystallographic analysis. Further purification of the extract led to the isolation of dumortenol 6,7-epoxide (554), for which the structure was assigned tentatively by comparison of its NMR spectra to those of 554. The name “dumortane” was given to this new skeleton. These new compounds were not

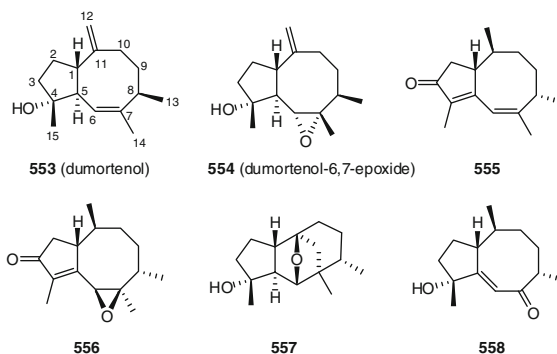


Fig. 4.10 *Dumortiera hirsuta*

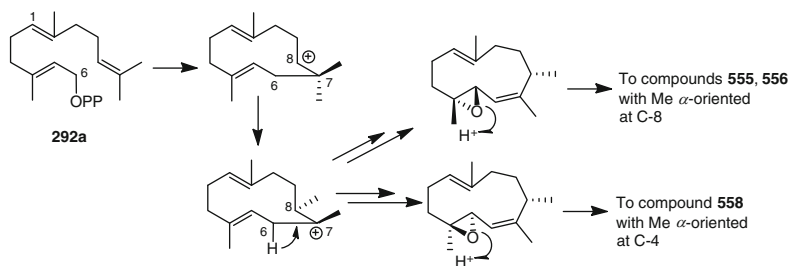


Scheme 4.10 Possible biogenesis pathways for dumortane-type sesquiterpenoids

present in a Japanese specimen of *D. hirsuta*. The dumortanes might be formed by the cyclization of *trans*-farnesyl diphosphate with migration of the methyl group, as shown in Scheme 4.10.



Dumortane- and rearranged dumortane-type sesquiterpenoids found in the Marchantiophyta



Scheme 4.11 Possible biogenesis pathways for dumortane-type sesquiterpenoids

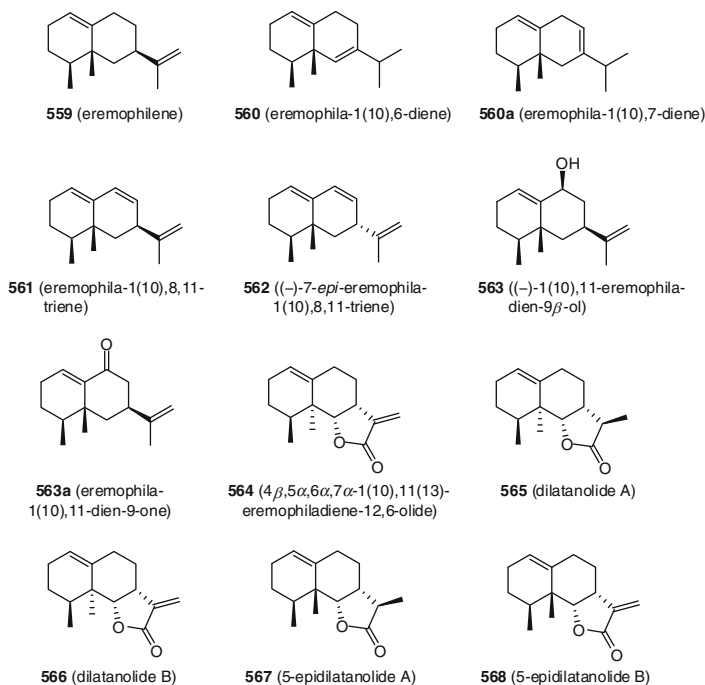
The ether extract of the Argentinian *D. hirsuta* was fractionated to give the two new dumortanes, **555** and **556**, a rearranged dumortane, **557**, and the nordumortane sesquiterpenoid, **558**, together with the previously known dumortanol (**553**). The structures of the new compounds were based on the analysis of their 2D-NMR data. The β -configuration of the epoxide of **556** was proved by its NOESY correlations. The HMBC spectrum of compound **557** showed the position of the tertiary methyl group at C-4, the oxygenated methine at C-6, and the presence of a tricyclic skeleton derived from the dumortane precursor, **553**. The gross structure of **558** was based on the comparison of NMR spectroscopic data with those of dumortanol (**553**). Complete ^1H NMR assignments were achieved by COSY, HSQC, HMBC, and NOESY experiments (96). Compound **555** was detected in the ether extract of the Indonesian *D. hirsuta* (424).

It is noteworthy that the relative configuration at C-8 in **553** differs from that proposed for compounds **555**–**558**, suggesting that in the biosynthetic step of methyl group migration from C-7, shown in Scheme 4.11, both methyl groups are able to migrate, leading to a different final opposite configuration at C-8.

4.2.25 *Eremophilanes and Valencanes*

Eremophilene (**559**) is common in *Frullania* and *Radula* species, and two species representing different genera, *Tritomaria polita* and *Trocholejeunea sandvicensis*, have been found also to elaborate **559**. Three diastereomers, eremophila-1(10),6-diene (**560**), eremophila-1(10),8,11-triene (**561**), and (–)-7-*epi*-eremophila-1(10),8,11-triene (**562**), were identified in the Japanese *Radula perrottetii*, *Frullania anomala*, *Marsupella emarginata*, and *Trocholejeunea sandvicensis*, as shown in Table 4.2.

Eremophila-1(10),7-diene (**560a**) was detected in an unidentified Indonesian *Frullania* species (426).

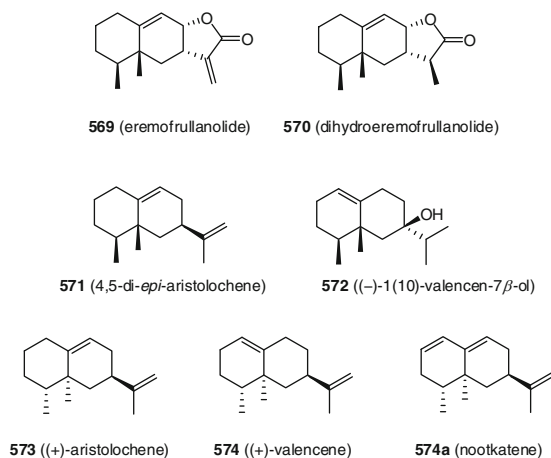


Eremophilane-type sesquiterpenoids found in the Marchantiophyta

Marchantia polymorpha produces a number of different secondary metabolites of the sesquiterpenoid, diterpenoid, and bis-bibenzyl types (39, 40). The German *M. polymorpha* subsp. *aquatica* was hydrodistilled to obtain an essential oil, which was purified by preparative GC to afford a new eremophiladienol (**563**). Chemical reaction and 2D-NMR spectroscopy confirmed that **563** is (–)-1(10),11-eremophiladien-9β-ol. Treatment of **563** with thionyl chloride gave eremophila-1(10),8,11-triene (**561**). This was followed by hydrogenation to afford eremophilane and valencane, which were obtained by hydrogenation of (–)-eremophilene (**559**). Oxidation of **563** with *Collins* reagent gave eremophila-1(10),11-dien-9-one (**563a**) (680).

A new eremophilanolide (**564**) from the dichloromethane extract of *Frullania muscicola* was obtained and its structure elucidated as 4β,5α,6α,7α-1(10),11(13)-eremophiliden-12,6-olide, by comparison of its NMR data with those of 5α,6α,10α,11β,13-dihydroeudesm-4(15)-en-12,6-olide (**666**) (443). This is only the second record of the isolation of both eudesmanolides and an eremophilanolide in a single liverwort species (40).

Two *ent*-eremophilanolides, dilatanolides A (**565**) and B (**566**), were isolated from a European specimen of *Frullania dilatata* together with eremofrullanolide (**569**) (40) and several new eudesmanolides. The IR and 2D-NMR spectra suggested that the γ -lactone (1775 cm^{-1} ; δ 180.4 ppm, s) unit of **565** could be assigned to an eremophilanolide. Difference NOE spectra of this compound were used to confirm its relative stereostructure. The absolute configuration was proven by the negative *Cotton* effect at 214 nm as observed in (+)-*ent*-frullanolide (**659**) and **681**. The structure of **566** was established by the similarity of ^1H and ^{13}C NMR data to those of **565** and the formation of the C-11 stereoisomer from dilatanolide A by NaBH_4 reduction (578). The rearranged sesquiterpene lactones **680**–**682** and the eremophilane C-12/C-6 olides **565** and **566** are the first such compounds to be isolated from the bryophytes. The Argentinean *Frullania brasiliensis* was fractionated to afford the two eremophilanolides, 5-*epi*-dilatanolide A (**567**) and 5-*epi*-dilatanolide B (**568**), together with *ent*-eudesmanolides, steroids, and bibenzyls. Conclusive evidence for the structure of **567** was based on X-ray crystallographic analysis. NaBH_4 reduction of **568** gave a dihydro derivative, for which the structure was elucidated as a C-11 epimer of **567** by X-ray crystallography. The absolute configurations of **567** and **568** were determined by the negative sign of their *Cotton* effects (98). Eremophilanolide (**569**), which causes potent allergenic contact dermatitis, and its dihydro derivative, **570** (39, 40), were detected in three *Frullania* species, namely, *F. lobulata*, *F. media*, and *F. probosciphora* (78). 4,5-Di-*epi*-aristolochene (**571**), a C-1(C-10)-diastereomer of eremophilene (**559**), was identified among the volatile components of certain *Frullania* (492), *Radula* (826), *Tritomaria* (18), and *Trocholejeunea* species (539).



Eremophilane- and valencane-type sesquiterpenoids found in the Marchantiophyta

Further investigation of the essential oil of *Lophozia ventricosa* resulted in the identification of 1(10)-valencen-7 β -ol (**572**) as a trace constituent (486). The essential oil obtained by hydrodistillation of the German *Lepidozia reptans* was analyzed by GC/MS to identify (–)-1(10)-valenecen-7 β -ol (**572**) and (+)-1(10)-spirovetiven-7 β -ol (**899**), which were isolated subsequently by preparative GC (681).

The essential oil obtained from *Dumortiera hirsuta* was analyzed by capillary column chromatography with a cyclodextrin stationary phase to identify aristolochene (**573**) and valencene (**574**), in 100% *ee* for both (–)-**573** and (+)-**574**. (+)-Aristolochene (**573**) was isolated from *Porella arboris-vitae* (707). The ether extracts of the Indonesian *D. hirsuta* and an unidentified Indonesian *Frullania* species were analyzed by GC/MS to indicate the presence of nootkatene (**574a**) (424).

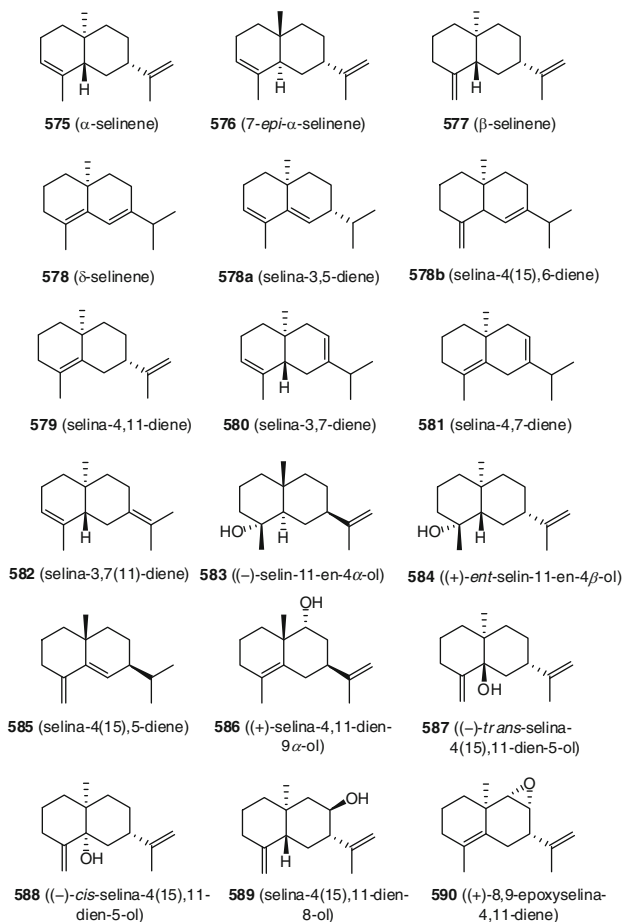
4.2.26 *Eudesmanes*

Liverworts produce various eudesmane- (= selinane)-type sesquiterpenoids, including lactones and lactone dimers. α -Selinene (**575**), β -selinene (**577**), δ -selinene (**578**), selina-4(11)-diene (**579**), and their enantiomers have been identified in many different species of the Jungermanniales, as shown in Table 4.2. The New Zealand *Tylimanthus tenellus* produced *ent*-eudesmanes, (+)-3,11-eudesmadiene (= α -selinene) (**575**), and (–)-4(15),11-eudesmadiene (= β -selinene) (**577**), which are enantiomeric to the same compounds when found in higher plants (896).

(–)-7-*epi*- α -Selinene (**576**) from *Dumortiera hirsuta* displayed a negative optical rotation and its *ee* was 100%. This compound was found in *Pellia epiphylla*, while its (+)-enantiomer was isolated from *Porella arboris-vitae* (707). The New Zealand *Marchantia foliacea* elaborates α -selinene (**575**) and γ -cadinene (**346**) as the major components, while *Marchantia pileata*, also collected in New Zealand, contained predominantly β -eudesmol (**601**) (72). (+)- δ -Selinene (**578**) and (–)-cascarilladiene (= eudesma-5,7-diene) (**596**) were detected in the essential oil of *Preissia quadrata* by GC/MS using capillary column chromatography on a heptakis(6-*O*-methyl-2,3-di-*O*-pentyl)- γ -cyclodextrin stationary phase (433).

(–)-Selina-11-en-4 α -ol (**583**) is the major component of the essential oil of *Conocephalum conicum*. In addition, (+)-selina-4,11-diene (**579**), a dehydrated product of **583**, was isolated from the same oil. Dehydration of **583** gave (–)- α -selinene (**575**), (+)- β -selinene (**577**), and (+)-selina-4,11-diene (**579**), with their absolute configurations determined on an enantioselective GC column using heptakis(6-*O*-*t*-butyldimethylsilyl-2,3-di-*O*-methyl)- β -cyclodextrin as stationary phase (543). Eudesm-3,7-diene (= selina-3,7-diene) (**580**) and its double bond isomer, selina-4,7-diene (**581**) were detected in a *Radula* species (826). *Pellia*, (492), *Radula* (826), and *Symphyogyna* species (492) produce the C-4/C-7

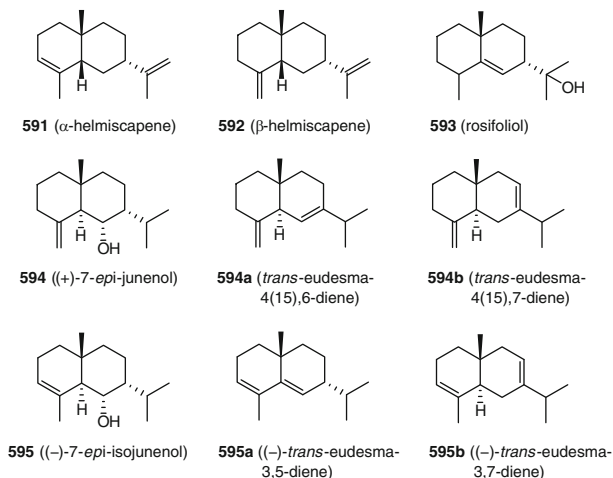
double bond isomer, **582**. *Adio* and associates detected four compounds in the eudesmanol series, (+)-selina-4,11-dien-9 α -ol (**586**), in *Marsupella aquatica*, and (–)-*trans*-selina-4(5),11-diene-5-ol (**587**), (+)-*cis*-selina-4(15),11-dien-5-ol (**588**), and (+)-8,9-epoxyselina-4,11-diene (**590**), in *M. alpina* (17). *ent*-Selin-11-en-4 β -ol (**584**) was isolated from an ether extract of *Riccardia nagasakiensis*, together with spathulenol (**136**), β -elemene (**283**), γ -cadinene (**346**), and longifolene (**779**) (141). The four last-mentioned compounds have been found in many other liverworts (40).



Eudesmane-type sesquiterpenoids found in the Marchantiophyta

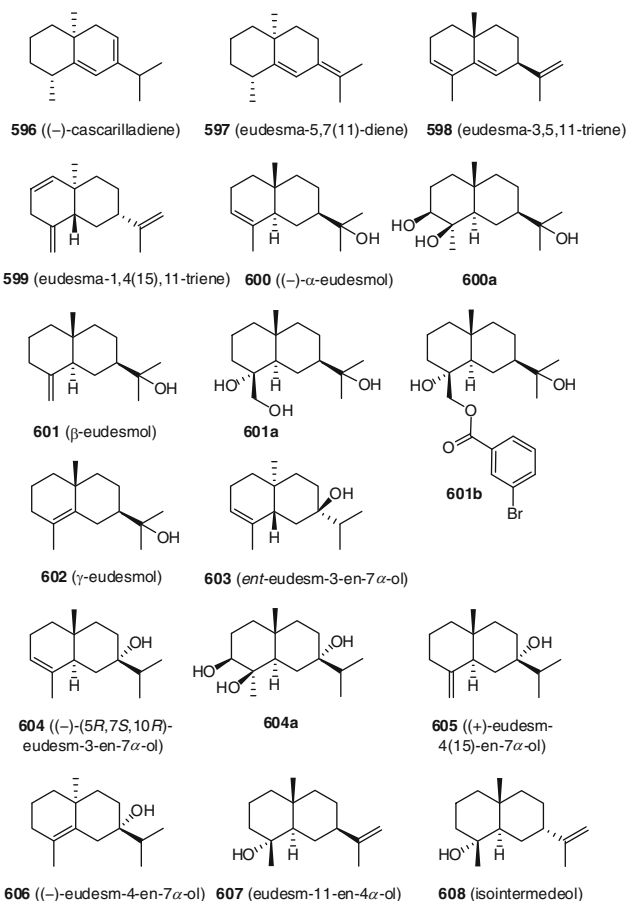
α -Helmiscapene (**591**) and β -helmiscapene (**592**) were isolated from the essential oil of *Radula perrottetii* (826). Both compounds were described also as eudesmane sesquiterpenoid constituents of the liverwort, *Scapania* species (28).

The essential oil obtained by hydrodistillation and the dichloromethane extract of the German *Calypogeia muelleriana* were analyzed by GC/MS, using a chiral adsorbent for separation, and then purified by preparative GC, to give (–)-rosifoliol (**593**), a compound not reported in the literature previously (933).



Eudesmane-type sesquiterpenoids found in the Marchantiophyta

Reinvestigation of the essential oil of *Tritomaria quinquedentata* showed the presence of a number of sesquiterpenoids including two new eudesmanes, (+)-7-*epi*-junenol (**594**) and (–)-7-*epi*-isojunenol (**595**). The structure of the latter compound was elucidated by a combination of 2D-NMR (HMBC, NOESY) data interpretation and the formation of (–)-*trans*-eudesma-3,5-diene (**595a**) and (–)-*trans*-eudesma-3,7-diene (**595b**) by dehydration. Compound **594** is known as a reaction product from 1 β -bromo-4 α -hydroxy-6 α -acetoxy-5 α ,6 β (*H*)-eudesmane (130, 857). Dehydration of **594** gave *trans*-eudesma-4(15),6-diene (**594a**) and *trans*-eudesma-4(15),7-diene (**594b**). The absolute configurations of both **594** and **595** were confirmed by the identification of the hydrogenated products from **595a**, **594a**, **594b**, and (+)- δ -selinene (**578**). Hydrogenation of **595a** gave four saturated eudesmanes, of which one proved to be identical to a hydrogenation product of **594a**, **594b**, and **578**. These eudesmanes showed the same MS, and exhibited the same retention times on achiral and chiral GC phases (928).



Eudesmane-type sesquiterpenoids found in the Marchantiophyta and their related compounds

GC/MS analysis of the ether extract of the Tahitian *Plagiochila* and *Symphyogyna brasiliensis* indicated the presence of eudesma-5,7(11)-diene (**597**) (494). *Marsupella alpina* also produces eudesma-1,5,11-triene (**598**) (17).

α-Eudesmol (**600**) has been isolated from many higher plants and liverworts, and typically has been assigned with a positive optical rotation, although the magnitude of the optical rotation reported in the literature for this compound is ambiguous. Thus, the absolute configuration and optical purity of (–)-α-eudesmol (**600**) isolated from the liverwort *Porella perrottetiana* (Fig. 4.11) strongly suggest that the specific rotation values described in many previous papers should be revised. The absolute configuration of (–)-α-eudesmol (**600**) was shown to be identical to that of (+)-β-eudesmol (**601**) found in higher plants. As a result of the preparation of



Fig. 4.11 *Porella perrottetiana*

600 from eudesm-3-en-7 α -ol (**603**) and the application of Mosher's method to the triol **600a** obtained from **600** by osmium-catalyzed dihydroxylation, it is clear that the published $[\alpha]_D$ value for (–)- α -eudesmol of $+28.5^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$ should be revised to $[\alpha]_D -6.4^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$. This is the first example of the isolation of (–)- α -eudesmol (**600**) in a pure state from a natural source (892).

The volatile component of Tahitian *Trichocolea pluma* contains γ -eudesmol (**602**) (494). *Lepidozia* elaborates various sesquiterpenes such as bicyclogermacranes and eudesmanes (40). The ether extract of *L. vitrea* was purified by passage over Sephadex LH-20 to afford four new eudesmanes, eudesm-3-en-6 α -acetoxy-7 α -ol (**615**), *ent*-eudesm-3-en-7 α -ol (**603**), eudesm-4(15)-ene-6 β ,7 α -diol (**612**), and eudesm-4(15)-en-7 α -ol (**605**), along with (+)-eudesm-3-ene-6 β ,7 α -diol (**614**) (163). The stereostructure of **615** was deduced by analysis of its 2D-NMR data by comparison with analogous information for **614**. Lithium aluminum hydride reduction of **615** gave eudesm-3-ene-6 α ,7 α -ol (**615a**), followed by PDC oxidation to afford a ketoalcohol, indicating a vicinal diol. The absolute configuration of **615** was established by means of the 1,2-diol complexation method. The CD spectrum employing Eu(fod)₃ as complexing reagent of **615a** showed the (6*R*)-configuration. Comparison of the spectroscopic data of **603**, **605**, and **612** with those of **612** and **615** confirmed their structures (871).

The ether extract of *Chilosyphus polyanthos* was fractionated on silica gel and Sephadex LH-20 to give four eudesmane sesquiterpenoids, **604**, **605**, **606**, and **613**. Compound **604** was demonstrated as being identical to (5*R*,7*S*,10*R*)-eudesm-

3-en-7 α -ol (**603**), isolated from the liverwort, *Lepidozia vitrea* (871), although the optical rotation of **603** showed an opposite sign, indicating that **604** is (5*S*,7*R*,10*S*)-eudesm-3-en-7 α -ol. GC/MS analysis of both compounds on a chiral phase showed different retention times. Conclusive evidence for the absolute configuration of **604** was obtained by a combination of X-ray crystallographic analysis of the triol **604a** prepared by catalytic asymmetric dihydration of **604** as well as the modified Mosher's method using (+)-(*R*)- and (–)-(*S*)- α -methoxy- α -trifluoromethylphenyl acetic acid (MTPA). Compound **605** was identical to that found in *L. vitrea*, except for the sign of the optical rotation. Enantio-differentiating GC/MS analysis of **605** demonstrated that both species contain a mixture of enantiomeric isomers (56:44% from *C. polyanthus*; 72:28% from *L. vitrea*). To distinguish between the (+)- and (–)-enantiomeric isomer, (+)-eudesm-4(15)-en-7 α -ol (**605**) was prepared from (+)- β -eudesmol (**601**) isolated from *Atractylodes lancea* rhizome. The absolute configuration of **601** was obtained from the X-ray crystallographic analysis of the *m*-bromobenzoate **601b** of the triol **601a** prepared by the catalytic asymmetric dihydration of **601**. (+)-Eudesm-4(15)-en-7 α -ol (**605**) was partially synthesized from β -eudesmol (**601**) in five steps.

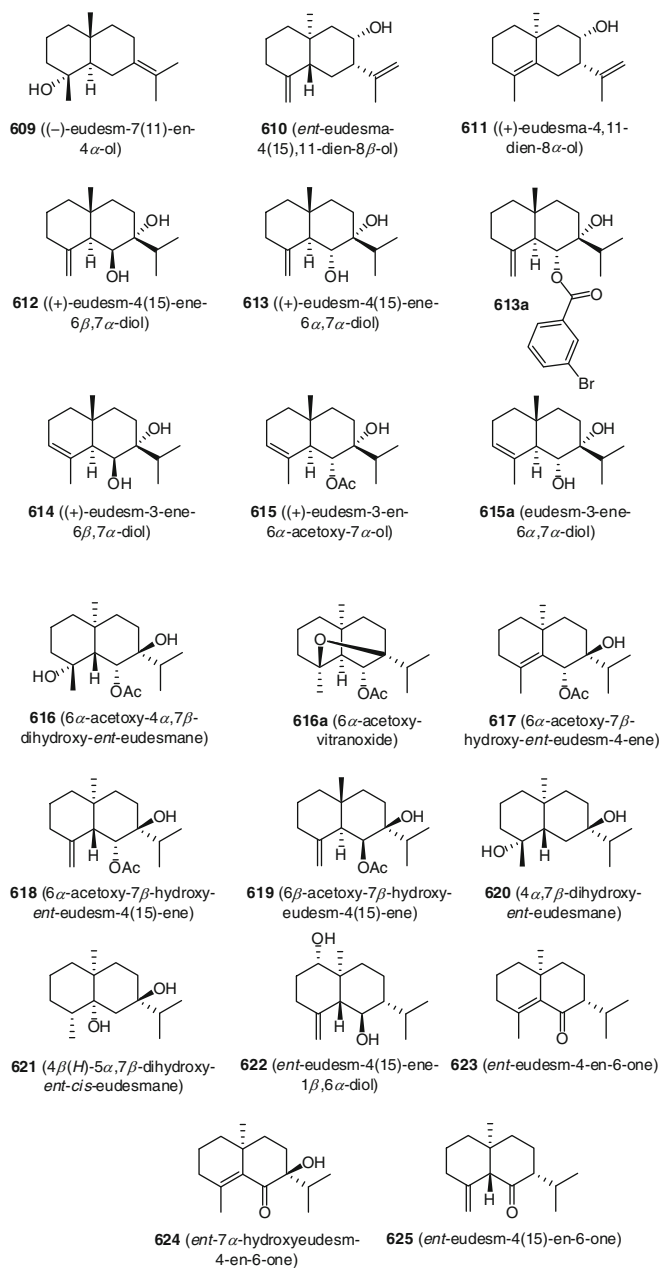
From the essential oil of the Taiwanese *Lepidozia vitrea*, three eudesmanes, (–)-eudesm-4-en-7 α -ol (**606**), eudesm-4(15)-en-7 β -ol (**605**), and (+)-eudesm-3-en-7 β -ol (**603**), were obtained (645, 890). The ether extract of the New Zealand *Marchantia foliacea* was purified by a combination of CC, Sephadex LH-20, and HPLC to afford the known eudesm-11-en-4 α -ol (**607**) (347).

Bioassay-directed fractionation of the methyl ethyl ketone extract of *Chiloscyphus rivularis* gave the known isointermideol (**608**) (827, 956). Previously, *ent*-eudesmanolides possessing a hot taste and cytotoxicity against epidermoid carcinoma cells have been found to occur in the crude extract of *Diplophyllum albicans*.

The new eudesmane sesquiterpenoid **610** was isolated from an ether extract of the New Zealand *Plagiochilion conjugatus*. Compound **610** was oxidized with PDC to give eudesm-4(15)-dien-8-one, which was treated with *p*-TsOH to afford the known (–)-*ent*- β -cyclogermacrene (**631**) (40), indicating that **610** is (–)-*ent*-eudesm-4(15),11-dien-8 β -ol (72, 616). Reinvestigation of the chemical constituents of the essential oil of the same liverwort resulted in the isolation of a new eudesmane alcohol, (+)-eudesma-4,11-dien-8 α -ol (**611**), and detection of the common sesquiterpene hydrocarbons β -acoradiene (**69**), anastreptene (**122**), aromadendra-1(10),4-diene (**164**), aromadendra-4,10(14)-diene (**166**), aromadendra-4,9-diene (**167**), β -barbatene (**235**), β -bazzanene (**261**), β -elemene (**283**), bicycloelemene (**290**), bicyclogermacrene (**293**), α -selinene (**575**), δ -selinene (**578**), maali-1,3-diene (**797**), and tritomarene (**916**), and the oxygenated sesquiterpenoids dehydroviridiflorol (**128**), globulol (**139**), 3 α -acetoxybicyclogermacrene (**298**), diplophyllin (**676**), *ent*-dihydrodiplophyllin (**677**), and *ent*-diplophyllolide (**678**).

The absolute configuration of **611** was determined by comparison of the retention times of its hydrogenated products with those of the hydrogenation products of authentic (+)- α -selinene (**575**) by GC on a chiral adsorbent (**15**). Compound **613** was identical to eudesm-4(15)-en-6 α ,7 α -diol, for which the absolute configuration remained to be clarified. The X-ray crystallographic analysis of the *m*-bromobenzoate (**613a**) prepared from **613** and analyzed by the modified Mosher method confirmed that the absolute stereochemistry of **613** is (5*R*,6*R*,7*R*)-eudesma-4(15)-en-6,7-diol. Compound **609** was identical to (–)-eudesm-7(11)-en-4 α -ol and the optical rotation and spectroscopic data were closely comparable to the same compound prepared from (+)- β -eudesmol (**601**). Thus, the absolute configuration of **609** was established as (4*S*,5*R*,10*R*)-eudesm-7(11)-en-4-ol. It is noteworthy that only **605** found in both the species *Chiloscyphus polyanthos* and *Lepidozia vitrea* was shown to be a mixture of enantiomers by GC/MS analysis using a chiral capillary column, although compounds **603**, **609**, and **613** were obtained in optically pure form. The above results indicated that (–)-chiloscyphone (**444**) and (+)-chiloscypholone (**445**) (see Sect. 4.2.18) might be biosynthesized from **613** via ring construction and methyl migration processes (**890**). *ent*- α -Selinene (**575**) was isolated from the German *C. polyanthos* (**27**). It seems reasonable to conclude that *C. polyanthos* collected in different locations possesses different sets of enzymes that act in mediating the cyclization process of the germacradiene intermediate leading to the eudesmanes. The ethanol extract of the Chinese liverwort, *Lepidozia vitrea*, was purified by CC to give the known eudesm-3-ene-6 β ,7 α -diol (**614**) and 7 α -hydroxyeudesm-3-en-6 α -yl acetate (**615**) (**497**, **871**).

Three new eudesmanes (**617**, **620**, and **621**) were isolated from the Taiwanese *Lepidozia fauriana* together with 6 α -acetoxy-4 α ,7 α -dihydroxy-*ent*-eudesmane (**616**), for which the structure was revised from the previously reported 6 β -acetoxyvitranoxide (**616a**) (**40**) by X-ray crystallographic analysis. The spectroscopic data of compounds **617** and **618** were closely comparable. The structure of **617** was confirmed by 2D-NMR data interpretation, inclusive of the NOESY spectrum. The previously reported structure of 6 β -acetoxy-7 β -hydroxyeudesma-4(15)-ene (**619**) isolated from *Bazzania tridens* (**152**) was revised to 6 α -acetoxy-7 β -hydroxy-*ent*-eudesma-4(15)-ene (**618**) from its NOESY spectrum. The relative configuration of **620** was clarified as being the same as that of **616** also using the NOESY spectrum. This same technique was used to determine the *cis* configuration at C-1 and C-5 in compound **621**. Thus, the structures of **620** and **621** were shown to be 4 α ,7 β -dihydroxy-*ent*-eudesmane and 4 β (*H*)-5 α ,7 β -dihydroxy-*ent*-*cis*-eudesmane, respectively (**747**). The physical and spectroscopic data of 4(15)-eudesman-1,6-diol (**622**), isolated from *Jackiella javanica*, were identical to those of (+)-4(15)-eudesman-1 β ,6 α -diol (**352**, **413**), except for the sign of the optical rotation. Thus, compound **622** is *ent*-4(15)-eudesman-1 β ,6 α -diol (**608**).



Eudesmane-type sesquiterpenoids found in the Marchantiophyta and their related compounds

GC and GC/MS analysis of the essential oil of *Plagiochila bifaria* showed the presence of eudesm-1,4(15),11-triene (**599**) and frullanolide (**658**). The essential oil was purified by preparative GC and yielded the three eudesmanes, **623–625**. The structure of **624** was identified as (–)-(7*S*,10*S*)-7-hydroxyeudesm-4-en-6-one by comparison of its spectroscopic data with those of an authentic sample. The (+)-isomer has been isolated from *Chloranthus spicatus* (**825**) and *C. serratus* (**398**), and its absolute configuration has been established as (7*S*,10*R*) (**398**). The negative sign of optical rotation of **624** suggested the (7*S*,10*S*) configuration. This assumption was confirmed on enantioselective GC by co-injection and the column residence time of (–)-**624**, when compared with an authentic sample of (+)-**624**, using β -cyclodextrin as the stationary phase. The structures of **623** and **625** were assigned as eudesm-4-en-6-one and eudesm-4(15)-en-6-one from their 2D-NMR (COSY, HMQC, HMBC) data and by the formation of **623** from **625** on thermal degradation. Compounds (+)-**623** and (+)-**625**, with the (7*S*,10*R*)- and (5*S*,7*S*,10*R*)- configurations, were also reported as *C. serratus* constituents (**398**). In order to clarify the absolute configurations of **623** and **625**, compound **623** was reduced by lithium aluminum hydride to give (+)-selina-3,5-diene (**578a**) and (–)- δ -selinene (**578**). Treatment of (–)-**625** with aluminum oxide as a catalyst provided **623**. The two eudesmanes **623** and **625**, like compound **624**, were elucidated as new natural products (**277**).

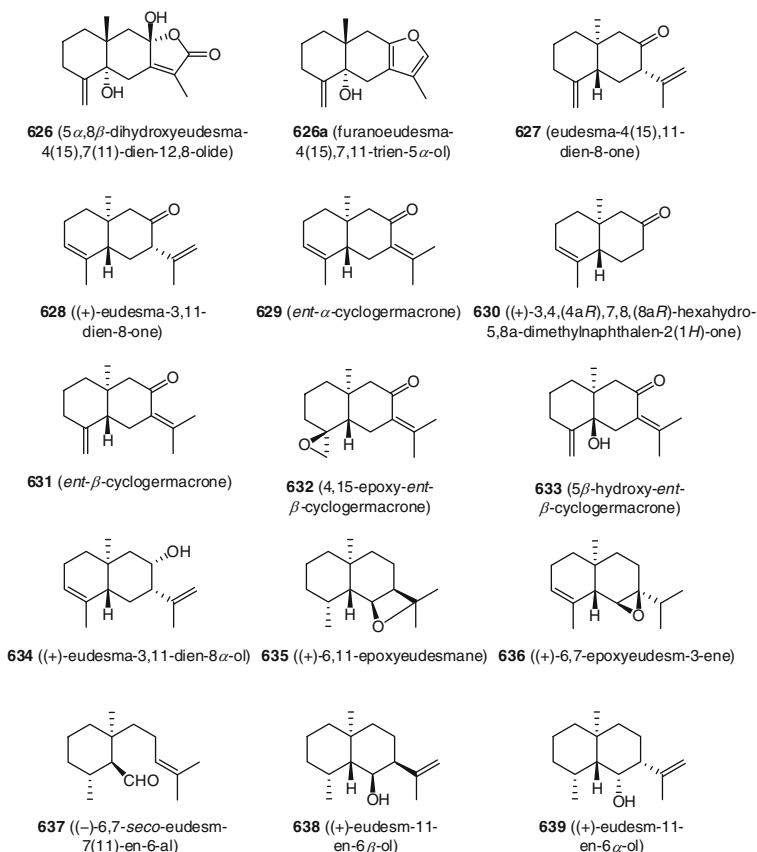
The essential oils of four *Plagiochila* species were analyzed by GC and GC/MS. *Plagiochila bifaria* elaborated *ent*-eudesm-4(15)-en-6-one (**625**) (9.3–18.7%) as a major component (**221**).

Lophocolea heterophylla is known for its mossy odor. This liverwort produces 5 α ,8 β -dihydroxyeudesma-4(15),7(11)-dien-12,8-olide (**626a**) (**40**). From the essential oil of the same species a new eudesmane, furanoeudesma-4(15),7,11-trien-5 α -ol (**626**), was isolated by preparative GC. When the essential oil in hexane was stored at 8°C for a few months, compound **626a** was formed (**746**). This type of autoxidation is well known to proceed from furanosesquiterpenoids to the corresponding lactones (**678**). Eudesma-4(15),11-dien-8-one (**627**), (+)-eudesma-3,7(11)-dien-8-one (**629**), (–)-eudesma-4(15),7(11)-dien-8-one (**631**), and (+)-6,7-epoxyeudesm-3-ene (**636**), were identified in the essential oil of *Lophozia ventricosa*, along with selina-4(15),11-dien-8-ol (**589**) and a trace of eudesm-4-en-7-ol (**606**) (**486**).

Fractionation of the ether extract of an unidentified New Zealand *Chiloscyphus* species led to the isolation of the two new eudesmenones, **632** and **633**, together with *ent*- α -cyclogermacrone (**629**) and (–)-*ent*- β -cyclogermacrone (**631**), which is the enantiomer of (+)- β -cyclogermacrone isolated from *Atractylodes japonica* (**206**). The optical purities of *ent*- β -cyclogermacrone (**631**) and its enantiomer were established as 100% *ee* by enantioselective GC analysis. The structures of the new eudesmanes **632** and **633** were proposed, in turn, as 4,15-epoxy-*ent*-cyclogermacrone and 5 β -hydroxy-*ent*- β -cyclogermacrone, by analysis of their 2D-NMR spectra and comparison with analogous data of the known cyclogermacrones **629** and **631** (**635**).

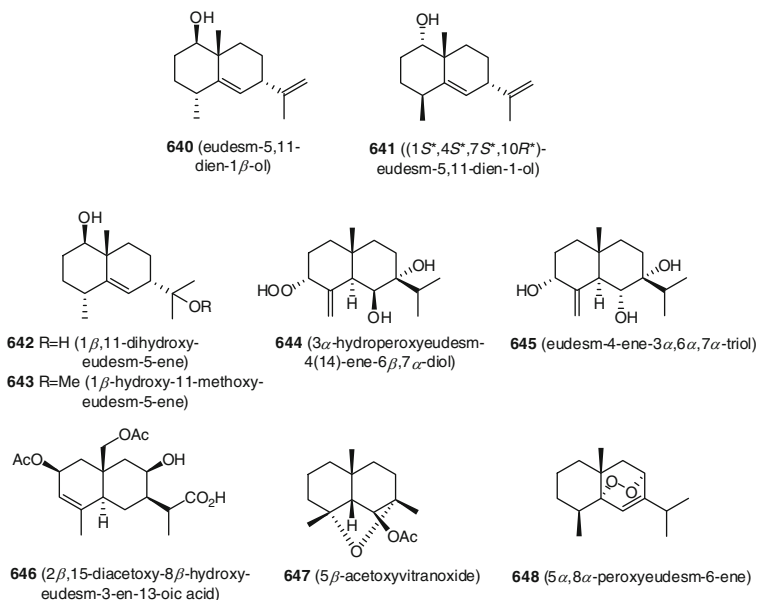
The New Zealand *Bazzania hochstetterii* elaborated the same eudesmane, (+)-eudesma-3,11-dien-8 α -ol (**634**) (**635**), as found in *B. spiralis* (**40**).

The essential oil obtained by hydrodistillation of *Tritomaria polita* was analyzed by GC and GC/MS to detect nine known sesquiterpene hydrocarbons as minor components. In turn, the major components were assigned as a group of new oxygenated sesquiterpenoids in the *ent*-eudesmane series, namely, (+)-eudesma-3,11-dien-8-one (**628**), (+)-eudesma-3,7(11)-dien-8-one (= α -cyclogermacrene) (**629**), (+)-3,4,3a*R*,7,8,8a*R*-hexahydro-5,8a-dimethylnaphthalen-2(1*H*)-one (a trinorsesquiterpene ketone) (**630**), (+)-eudesma-3,11-dien-8 α -ol (**634**), (+)-6,11-epoxyeudesmane (**635**), (–)-6,7-*seco*-eudesma-7(11)-6-en-al (**637**), (+)-eudesm-11-en-6 β -ol (**638**), and eudesm-11-en-6 α -ol (**639**), which occurred together with (+)-eudesma-5,7(11)-diene (**597**). The optical rotations of these new compounds were determined and their absolute configurations were assigned by enantioselective GC using a cyclodextrin capillary column in conjunction with chemical conversion, mainly through a hydrogenation reaction. Treatment of **628** with activated basic alumina gave compounds **629** and **630**. On GC analysis, compound **628** was degraded to give 8% of the more stable **629**. The enantiomer of **629** was isolated from the liverwort *Bazzania fauriana* (**40**). The reduction of **628** with LiAlH₄ gave an alcohol, which was identical with *ent*-eudesma-3,11-dien-8 α -ol (**634**) isolated from the liverwort *Bazzania spiralis* (**40**). Hydrogenation of (+)- α -selinene (**575**) and (+)-(**634**) gave the same perhydro derivatives, indicating that the absolute configuration of **634** is the same as that of (+)- α -selinene. Compound **635** was treated with Amberlist[®] resin to give (+)-eudesma-5,7(11)-diene (**597**), (–)-6,7-*seco*-eudesma-7(11)-en-6-al (**637**), (+)-eudesm-11-en-6 β -ol (**638**), and eudesm-11-en-6 α -ol (**639**), which coexist in the same plant. Compounds **638** and/or **639** might be the precursor of the *seco*-aldehyde **637**. The presence of (–)- δ -selinene (**578**) confirmed the absolute configuration at C-10 of **635**. Compound **637** was treated with an acidic ion-exchange resin to afford (–)-**578** and (–)-**639**, of which the latter compound co-occurred in the same plant, providing support for the absolute configuration of **637** at C-4 and C-10. The configurations proposed for H-5, H-6, and H-7 of both **638** and **639** were based on their NOESY NMR spectroscopic data (**18**). Further investigation of the essential oil of *Lophozia ventricosa* resulted in the isolation of a new eudesmane, (+)-6,7-epoxyeudesm-3-ene (**636**). Treatment of **636** and (+)- α -selinene with Amberlyst[®] resin, followed by hydrogenation, gave perhydrogenated products, for which enantioselective GC analysis showed that **636** possesses the same absolute configurations at C-5, C-7, and C-10 as those of (+)- α -selinene (**575**) (**486**).



Eudesmane-type sesquiterpenoids found in the Marchantiophyta

The methanol extract of the Patagonian *Adelanthus lindenbergianus* gave eudesmanes **640–643** together with an epoxyaristolane (**120**) (116). Compounds **640–643** might be artifacts obtained from aristolane (**120**) since these substances were obtained from the latter compound by acid treatment previously (196) (see Sect. 4.2.3). The ether extract of the New Zealand *Gackstroemia* species produced a new eudesmane alcohol, 1 α -hydroxy-5,11-eudesmadiene, with its relative structure assigned as (1*S**,4*S**,7*S**,10*R**)-eudesm-5,11-dien-1-ol (**641**) on the basis of the NOESY spectra of the original compound (**641**) and its benzoate (615). The diastereomer, (1*R**,4*R**,7*S**,10*R**)-eudesm-5,11-dien-1-ol (**640**), was isolated from the liverwort *Adelanthus lindenbergianus*, as mentioned above.



Eudesmane-type sesquiterpenoids found in the Marchantiophyta

An ethanol extract of the Chinese *Chiloscyphus polyanthus* was purified by CC to give the eudesmanes **644** and **645**. From its 1D- and 2D- (HMBC, DEPT, NOESY) NMR data analysis, together with HREIMS, compound **644** was assigned as 3 α -hydroperoxyeudesm-4(14)-ene-6 β ,7 α -diol. The gross structure of **645** was also proposed by 2D-NMR methods. The orientations of three hydroxy groups at C-3, C-6, and C-7 were deduced from the NOESY spectrum. Thus, the structure **645** of was proposed as eudesm-4-ene-3 α ,6 α ,7 α -triol (498).

Fractionation of an ether-soluble extract of the New Zealand *Marsupidium epiphytum* resulted in the isolation of a new eudesmane (**646**). Two acetates, a secondary hydroxy, and a carboxylic acid group were deduced as functional groups present from the IR and NMR spectra of this molecule. The location of each group and the complete structure were established as 2 β ,15-diacetoxy-8 β -hydroxyeudesm-3-en-13-oic acid (**646**) by a combination of COSY, HMQC, HMBC and NOESY spectroscopic data analysis (635). Previously, Shu and coworkers reported the isolation and structure elucidation of a new sesquiterpene ether named (+)-6 β -acetoxyvitranoxide (**647**) from the Taiwanese *Lepidozia vitrea* and *L. fauriana* (745). Conclusive evidence for the structure of **647** was based on the analysis of the COSY, HMBC, and NOESY NMR spectroscopic data (746).

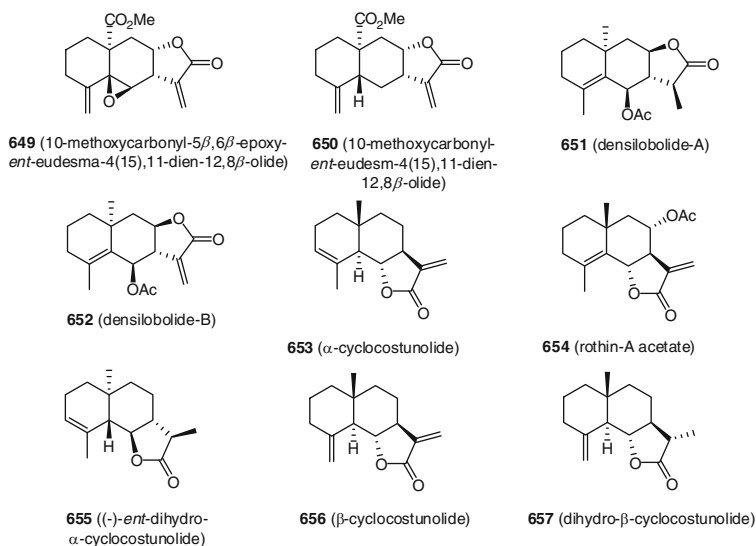
5 α ,8 α -Peroxyeudesm-6-ene (**648**) has been isolated from the liverwort *Chiloscyphus subporosus*. This compound has been previously isolated from the higher plant, *Isocoma coronopifolia* (Asteraceae) without complete assignments or

measurement of its optical rotation value (197). The presence of a peroxy moiety was confirmed by IR and by TLC visualization with *N,N*-dimethyl-1,4-phenylene-diammonium dichloride. Support for the structure of this compound was obtained by full interpretation of its 2D-NMR spectra (606).

The genus *Frullania* is a very rich source of sesquiterpene lactones (39, 40, 45). In the past 15 years, the lactones **651–675** and **680–682** were isolated from or detected in *Frullania* species.

The two new eudesmane sesquiterpene lactones, **649** and **650**, were isolated from the ether extract of the New Zealand *Plagiochilium conjugatus*, together with (–)-*ent*-eudesm-4(15),11-dien-8 β -ol (**610**) (72, 616). The CD spectrum of 10-methoxycarbonyl-*ent*-eudesm-4(15),11-dien-12,8 β -olide (**650**), for which the relative stereostructure was deduced using its 1D- and 2D-NMR spectroscopic data, showed a positive Cotton effect at 260 nm, indicating that the absolute structure is (–)-10-methoxycarbonyl-*ent*-eudesm-4(15),11-dien-12,8 β -olide (**650**). The structure, 10-methoxycarbonyl-5 β ,6 β -epoxy-*ent*-eudesm-4(15),11-dien-12,8 β -olide for compound **649** was deduced by comparison of its ^1H NMR spectroscopic data with those of **650** and analysis of its 2D-NMR (HMBC) spectrum (616). Previously, the isolation of *ent*-eudesmanes and aromadendranes was reported from *P. conjugatus* (40). Further fractionation of the ether extract of *Frullania densiloba* collected in a different location provided (–)-*ent*-dihydro- α -cyclocostunolide (**655**), densilobolide-A (**651**), and densilobolide-B (**652**). Compounds **651** and **652** were also detected in the ether extract of an unidentified *Frullania* species (424).

The detailed analysis of its COSY and HMBC spectra showed that **655** is identical to (+)-dihydro- α -cyclocostunolide, prepared from α -santonin, except for the sign of the optical rotation. Thus, it is apparent that **655** is the enantiomer of this semi-synthetic product. The eudesm-12,8-olide skeleton of **651** was postulated by analysis of the ^1H and ^{13}C NMR data and the relative configuration was demonstrated from the NOE difference spectra. Conclusive evidence for the structure **651** was obtained by X-ray crystallographic analysis. Reduction of **652** with NaHB_4 gave a dihydro derivative, for which the spectroscopic data were identical to those of **651**, indicating that **652** is a C-11 (C-13)-dehydro derivative. On considering their co-occurrence with *ent*-dihydro- α -cyclocostunolide (**655**), the absolute configurations of **651** and **652** were assumed to be the same as that of **655** (589). The ether extract of an unidentified *Frullania* species collected in Venezuela was purified by CC and preparative TLC to give (+)- α -cyclocostunolide (**653**) and rothin A acetate (**654**) (40, 843). The New Zealand *Frullania chevalierii* produces dihydro- β -cyclocostunolide (**657**) (78).

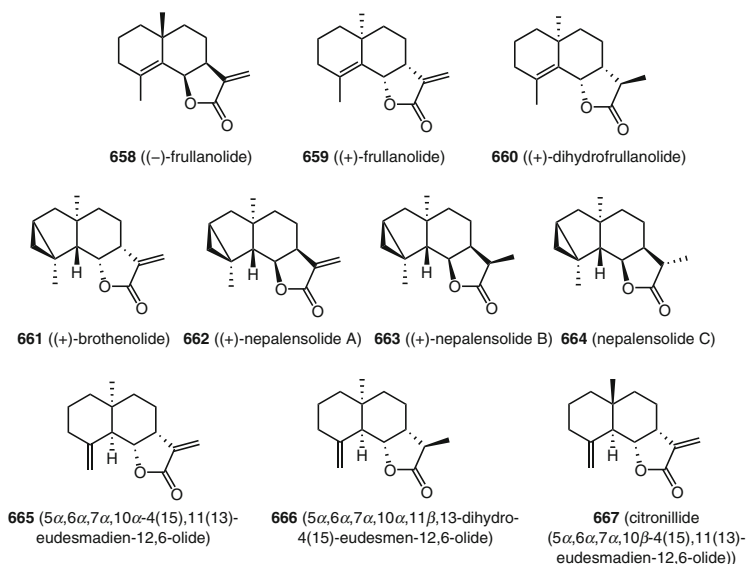


Eudesmane-type sesquiterpenoids found in the Marchantiophyta

The methanol extract of *Frullania nisqualensis* gave (–)-frullanolide (**658**), a compound that is known to cause strong allergenic contact dermatitis ([410](#)). Fractionation of the Argentinean *Frullania brasiliensis* (Fig. [4.12](#)) led to the isolation of the previously known (+)-frullanolide (**659**), nepalensolide C (**664**), nepalensolide A (**662**), and (+)-dihydrofrullanolide (**660**), together with two eremophilanolides, **567** and **568**. The conclusive structure of **664** was confirmed by X-ray crystallographic analysis ([98](#)). Brothenolide (**661**) and nepalensolides A (**662**) and B (**663**) were also isolated from *F. convoluta* ([226](#)).

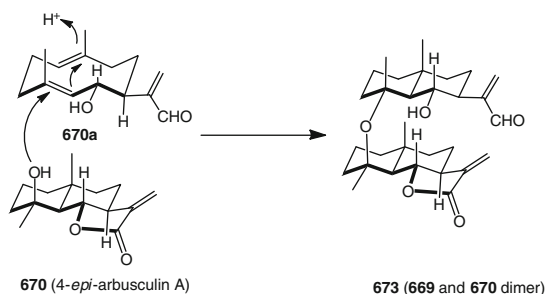


Fig. 4.12 *Frullania brasiliensis*. (Permission for the use of this figure has been obtained from Prof. Dr. Rob Gradstein, Paris, France)

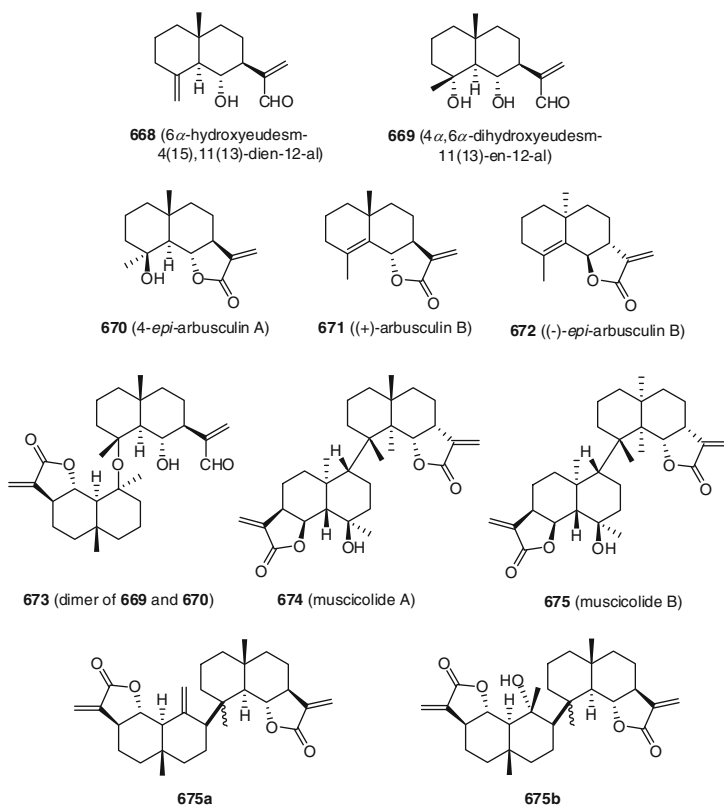


Eudesmane-type sesquiterpenoids found in the Marchantiophyta

The ether extract of the Japanese *F. tamarisci* ssp. *obscura* was fractionated to yield the sesquiterpene aldehyde **669** and a dimeric eudesmanolide (**673**), with two known eudesmanes, 4-*epi*-arbusculin A (**670**) and 6 α -hydroxyeudesma-4(15),11(13)-dien-12-al (**668**), also obtained. The structure of eudesmanal (**669**) was proposed by comparison of its spectroscopic data with those of **668**, and NOESY cross peaks were observed between H-14 and H-6, and H-15 and H-6, indicating that two methyl groups at C-4 and C-10 and a carbinyl proton at C-6 were in the *axial* configuration. The ^1H NMR spectrum of compound **673** showed signals attributable to a 1:1 mixture of **669** and **670**. However, the comparative TLC analysis of **673** with **669** and **670** showed different R_f values. As the mass spectrum showed a molecular ion at m/z 484, it became clear that **673** is a dimer of **669** and **670**. This hypothesis was confirmed by treatment of **673** with *p*-TsOH to give **669** and **670**, for which the optical rotation and spectroscopic data were identical to those of the naturally occurring monomeric substances. The relative configuration of **673** was established from the NOESY spectrum, which exhibited cross peaks between the hydroxy groups at C-6 and H-6' and the methyl group at C-14' (**886**). A biogenesis pathway for **673** is shown in Scheme 4.12.



Scheme 4.12 Formation of the eudesmane-type sesquiterpene dimer **673**

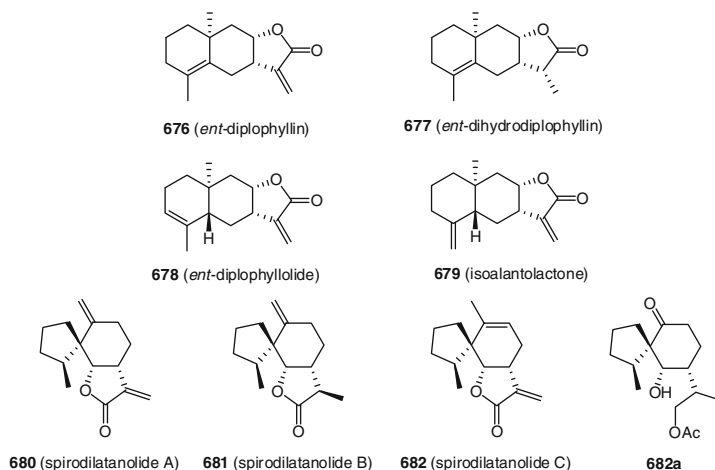


Eudesmane-type sesquiterpenoids found in the Marchantiophyta

F. tamarisci subsp. *tamarisci*, when stored for a year, was found to contain related eudesmane dimers with a C-C bond at C-3 and C-4' of costunolide (**709**) (**159**). Compound **673** was isolated from a fresh sample of *F. muscicola*.

The volatile components of *Frullania tamarisci* subsp. *obscura* were reinvestigated by GC/MS to detect 4-*epi*-arbusculin A (**670**), α -cyclocostunolide (**653**), and β -cyclocostunolide (**656**) as the major constituents (**492**). Diplophyllin (**676**) was isolated from *Anastrophyllum donnianum* (**139**). (–)-Diplophyllin (**676**) was obtained from the European *Scapania nemorea* (**569**) and the Tahitian *Mastigophora diclados* (**425**). This was the first time eudesmane sesquiterpenoids were isolated from species in the genera *Scapania* and *Mastigophra*. (–)-*ent*-Diplophyllolide (**678**), the double bond isomer of **676**, was isolated from *M. diclados* and *Diplophyllum*, *Lophocolea*, *Marsupella*, and *Tritomaria* species belonging to the Jungermanniales, as shown in Table 4.2.

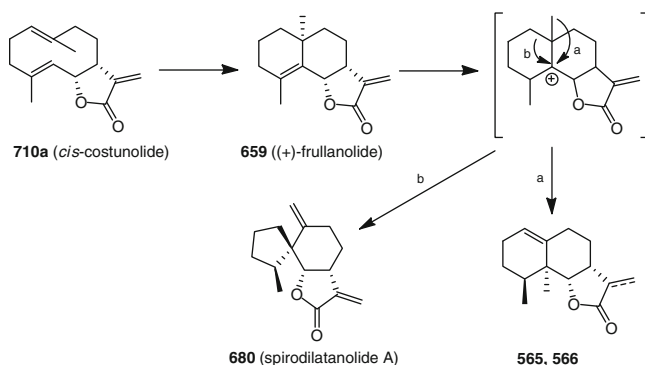
The ether extract of *Trocholejeunea sandvicensis* was analyzed by GC/MS to identify dihydrodiplophyllin (**677**). This was the first detection of a eudesmane sesquiterpenoid from this species (**492**).



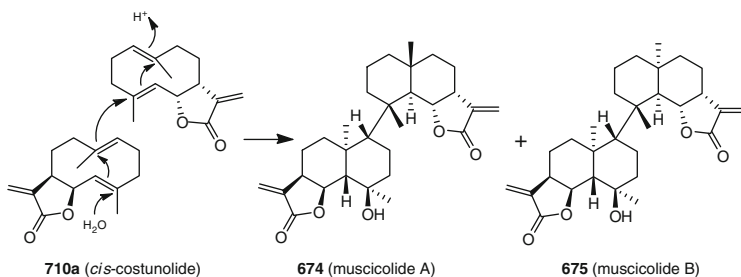
Eudesmane- and spiroeudesmane-sesquiterpenoids found in the Marchantiophyta

Three rearranged *ent*-spiroeudesmanolides, spirodilatanolides A (**680**), B (**681**), and C (**682**), were isolated from the European *Frullania dilatata*, together with (+)-frullanolide (**659**), critonilide (**667**), and eremofrullanolide (**569**) (40). Analysis of the 2D-NMR data and single-crystal X-ray diffraction were used to confirm the relative stereochemistry of **680**. Its absolute configuration was derived from an observed negative *Cotton* effect of the ketone **682a** prepared from **680** by reduction, acetylation, and ozonolysis. Compound **681** is the dihydro derivative of **680**, as confirmed by the absence of an α -methylene group at C-11/C-13. The (*R*)-configuration at C-11 was established by means of the NOESY spectrum. Reduction of **680** by NaBH₄ gave a dihydro derivative possessing the (*S*) configuration at C-11. The CD spectrum of **681** showed a negative *Cotton* effect. On the basis of the above data, the absolute configuration of **681** could be established. The spectroscopic data of **682** were similar to those of **680**, except for evidence of the presence of a vinyl methyl group in place of an exomethylene, indicating that **682** is a double bond isomer at C-10. Isomerization of **680** by trifluoroacetic acid gave **682**, so the absolute configuration of this product was confirmed (578). The spiro lactones **680–682** might be formed from *cis*-costunolide (**710a**) via (+)-frullanolide (**659**), as shown in Scheme 4.13.

Fractionation of the ether extract of the Ecuadorian *Frullania convoluta* resulted in the isolation of (–)- α -cyclocostunolide (**653**), (–)-dihydro- α -cyclocostunolide (**655**), (+)-brothenolide (**661**), (+)-nepalensolide A (**662**), and (+)-nepalensolide B (**663**), along with the new germacranolide *epi*-isocostunolide (**708**) (see Sect. 4.2.28) (226). The ethanol extract of the New Zealand *Hepatostolonophora paucistipula* was fractionated to afford (–)-*ent*-arbusculin B (**672**) together with (–)-*ent*-costunolide (**710**) (92). This is the first report of enantiomeric costunolide from Nature. (+)-Costunolide (**709**) has been found not only in liverworts (40), but also many higher plants. The compounds (+)-**671** and (–)-*ent*-arbusculin B (**672**) have been isolated from *Frullania* species (39, 40).



Scheme 4.13 Possible biogenesis pathways for eremophilanolides and a spiro lactone



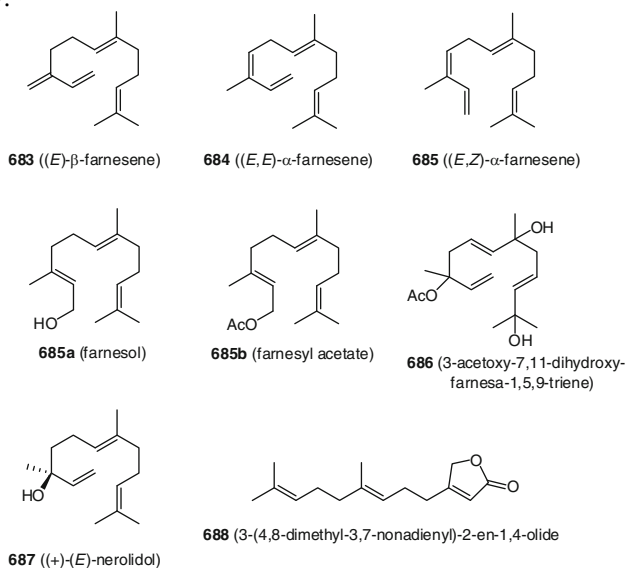
Scheme 4.14 Formation of eudesmane-type sesquiterpene dimers

The fractionation of the dichloromethane extract of *Frullania muscicola* resulted in the isolation of two new *cis*-annulated 12,6-eudesmanolides, **665** and **666**, and two new dimeric eudesmanolides, muscicolides A (**674**) and B (**675**), together with (+)-frullanolide (**659**), (+)-arbusculin B (**671**), and critonilide (**667**) (40). Confirmation of the *cis*-annulation of the two six-membered rings in **665** and **666** was arrived at by the presence of a NOE cross peak between H-5 and C10-Me for both compounds. The configuration of C-12 was proven in each case by a NOE experiment. The ¹H NMR spectrum of **674** showed two sets of signals for the H-5, H-6, H-7, H-13a, and H-13b protons of this 12,6-olide derivative. The ¹H-¹H COSY spectrum was used to establish two partial sequences of the protons belonging to monomers A (C-1–C-15) and B (C-1'–C-15'). The connectivity of two eudesmanolide monomeric units in the molecule of **674** was based on the ¹H-¹³C COSY, long-range ¹H-¹³C COSY, and NOE difference NMR spectra. The full structure of the second dimeric lactone (**675**) with a *cis*-junction between C-5 and C-10 was also based on the analysis of 2D-NMR data with the use of appropriate NOE experiments. Compounds **674** and **675** might be biosynthesized by the dimerization of two *cis*-costunolide (**710a**) units, as shown in Scheme 4.14 (443). Previously, the two eudesmanolide dimers **675a** and **675b**, having a C-3-C-4' connectivity, were isolated from the European *Frullania tamarisci* and their structures identified (40, 159). Such eudesmane dimers tend to be produced

during the long storage of their monomers. However, compounds **674** and **675** were found in fresh *F. muscicola*, so that the length of storage does not seem to be important for the formation of these particular structurally interesting eudesmane dimers.

4.2.27 Farnesanes

(*E*)- β -Farnesene (**683**) is the most common farnesane-type sesquiterpenoid in liverworts. As seen in Table 4.2, it is distributed throughout 20 Jungermanniales species. *Dumortiera hirsuta* was hydrodistilled to obtain an essential oil, which was analyzed by capillary column chromatography on a cyclodextrin phase to identify **683**. Compounds (*E,E*)-(**684**) and (*E,Z*)- α -farnesene (**685**) are also present in *Plagiochila* and *Radula* species, and *Dumortiera* and *Frullania* species, respectively.



Farnesane-type sesquiterpenoids found in the Marchantiophyta

Ludwiczuk and associates analyzed an ether extract of the Mexican *Asterella echinella* by GC/MS to confirm the presence of 3,7,15-trimethyl-2,6,10-dodecatrien-1-ol (= farnesol **685a**) and its acetate (= farnesyl acetate **685b**) (492).

3-Acetoxy-7,11-dihydroxyfarnesa-1,5,9-triene (**686**) was isolated from *Gackstroemia decipiens*. Oxygenated farnesane sesquiterpenoids like **683** are very rare (251). (+)-(*E*)-Nerolidol (**687**) was purified from the New Zealand *Jamesoniella tasmanica* (872), *Plagiochila ovalifolia* (84), and two Marchantiales species, *Corsinia coriandrina* (921) and *Lunularia cruciata* (79).

The ether extract of a Venezuelan unidentified *Frullania* species was purified by CC and preparative TLC to give 3-(4,8-dimethyl)-3,7-nonadienyl)-2-en-1,4-olide

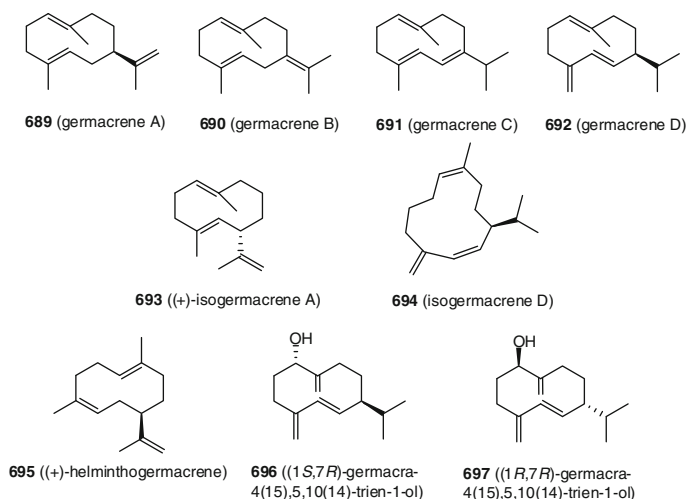
(**688**) ([843](#)). This is the first report of the isolation of this compound from a natural source, although it has been reported as a synthetic intermediate ([417](#)).

4.2.28 Germacranes

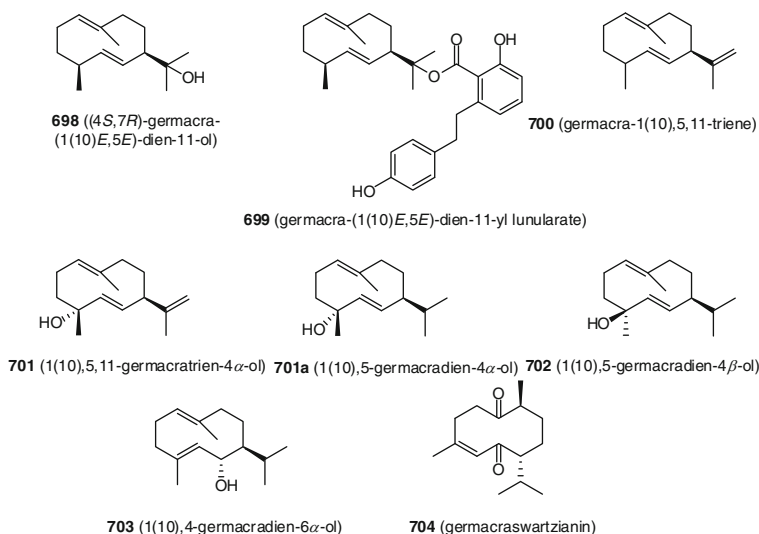
Germacrene C (**691**), a labile sesquiterpene hydrocarbon, was isolated from the essential oil of the German *Preissia quadrata* by preparative GC as a major component, together with germacrene D (**692**, 86% ee) ([433](#)).

Further investigation of the essential oil of *Lophozia ventricosa* resulted in the identification of germacrene B (**690**) in trace amounts ([486](#)). Germacrene B (**690**) was also detected by GC. Germacrene C (**691**) was converted by *Cope* rearrangement at 100°C to δ -elemene (**282**), and, under acidic conditions, it afforded δ -selinene (**578**) and selina-4(15),6-diene (**578b**) ([433](#)). (+)-Germacrene D (**692**) was isolated from the Japanese *Jamesoniella javanica* ([587](#)) and *Preissia quadrata* ([433](#)). It is noteworthy that the higher plants, *Solidago canadensis*, *S. gigantea*, and *S. altissima* accumulate both enantiomers of germacrene D (**692**) ([142](#)). *Schmidt* and associates reported the isolation and characterization of two enantioselective germacrene synthases from *S. canadensis* ([718](#), [719](#)).

A reinvestigation of the essential oils of *Saccogyna viticulosa* resulted in the isolation of isogermacrene A (**693**). Due to the instability of **693**, which gave the *Cope*-rearranged product **285** under comparable conditions to germacrene A (**689**), only a minor amount of **693** was isolated by preparative GC. Although 2D-NMR data could not be obtained, its structure was deduced from its coexistence in the plant with compound **285**. Treatment of **693** with an acidic ion-exchange resin gave maali oxide (**722**), β -gorgonene (**718**), and α -gorgonene (**717**), in the ratio 1:5:2. From the known absolute configurations of (–)-**722** and (+)-**718**, the (*S*)-configuration was deduced for (+)-isogermacrene A (**693**) ([276](#)).



Germacrane-type sesquiterpenoids found in the Marchantiophyta



Germacrane-type sesquiterpenoids found in the Marchantiophyta

The ether extract of an unidentified Tahitian *Jungermannia* species was analyzed by GC/MS to detect germacrene D (**692**) and bicyclogermacrene (**293**) as major components, and isogermacrene D (**694**) and 6 α -hydroxygermacra-1(10),4-diene (**703**), as minor components (494). Application of the HS-SPME (head space-solid phase microextraction) technique coupled with GC/MS analysis to the detection of volatile components of *Drepanolejeunea madagascariensis*, and showed the presence of germacrene D (**692**) (247). (+)-Helminthogermacrene (**695**), the (4*Z*)-isomer of germacrene A (**689**), was obtained from the German *Scapania undulata*. This compound was isolated for the first time as a natural product (16).

The Swiss *Barbilophozia floerkei* elaborates the germacrane-type alcohol, (–)-(1*S*,7*S*)-germacra-4(15),5,10(14)-trien-1-ol (**696**) (583). The sign of the optical rotation of **696** was in agreement with that of the same compound isolated from the brown alga, *Dilophus fasciola* (211). Its enantiomer, (1*R*,7*R*)-germacra-4(15), (5*E*),10(14)-trien-1-ol (**697**), has been isolated from the liverwort *Jackiella javanica* (40, 614). This is an example of the same liverwort producing both enantiomers of a secondary metabolite.

The ether extract of the Japanese *Dumortiera hirsuta* contained the known (4*S*,7*R*)-germacra-(1(10)*E*,5*E*)-dien-11-ol (**698**) (883), which was isolated from *Streptomyces citreus* (244). This same compound has been isolated from the ether extract of *Conocephalum conicum* (84). The absolute configuration of **698** was confirmed by a combination of X-ray crystallographic analysis and comparison with the optical rotations of two enantiomeric 1,5-diacetoxy-2-methylpentanes obtained from **698** and (–)- β -citronellene, by ozonolysis, acetylation, and then reduction by NaBH₄. When compound **698** was allowed to stand at room temperature for a long time, it readily converted to 5,11-epoxycadin-10 α -ol (**365**), **698a**, and **698b** (Scheme 4.4). During a study of the constituents of *D. hirsuta*, compound

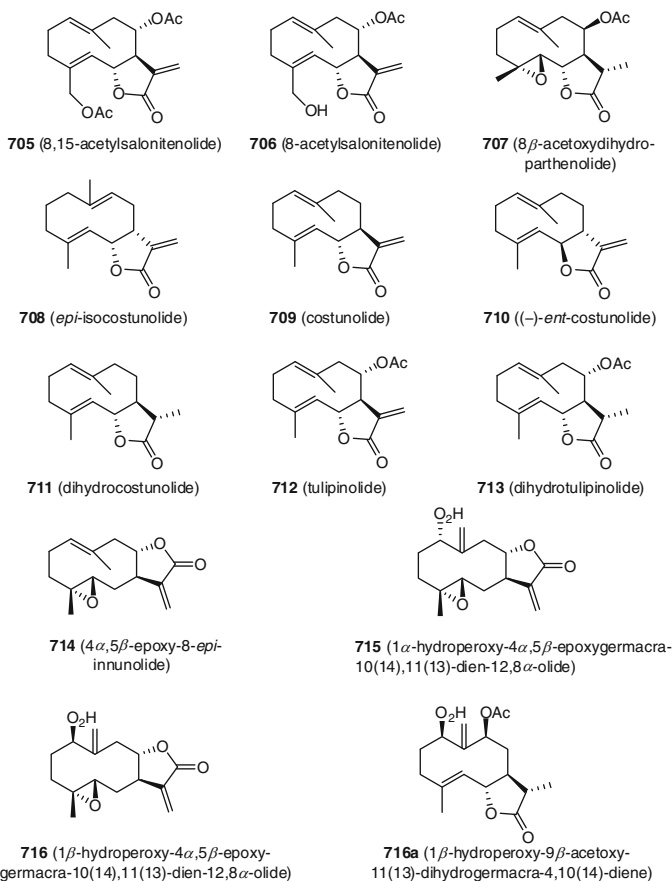
365 was isolated from a crude extract that had been stored for some time. It was thus suggested that **365** was generated as an artifact.

The ether extract of the Costa Rican *Bryopteris filicina* produced two germacranes, germacra-(1(10)*E*,5*E*)-dien-11-ol (**698**) (244, 604) and 1(10),5,11-germacatrien-4 α -ol (**701**) (179, 604), which were not found in the same species collected in Panama (576). Germacra-(1(10)*E*,5*E*)-dien-11-ol (**698**) is one of the known constituents of *Conocephalum conicum* (543). The Japanese *C. conicum* produced germacra-(1(10)*E*,5*E*)-dien-11-ol (**698**) (543, 880), which was also detected in *Dumortiera hirsuta* (40).

The *n*-hexane extract of *Marchantia emarginata* subsp. *tosana* was fractionated over silica gel to afford a new germacrene ester, germacra-1(10),5-dien-11-ol ester (**699**), $[\alpha]_D -46.5^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$, together with germacra-1(10),5-dien-11-ol (**698**) and germacra-1(10),5,11-triene (**700**). The structure of **699** was assigned as germacra-(1(10)*E*,5*E*)-dien-11-yl lunularate on the basis of the interpretation of its 2D-NMR spectroscopic (COSY HMBC, HMQC, NOESY) data. Other pieces of key evidence were the ester carbonyl (1720 cm^{-1}) signal in the IR spectrum and a fragment peak at m/z 228 formed by *McLafferty* rearrangement in the MS (347).

Further fractionation of the dichloromethane extract of *Porella canariensis* collected in Madeira resulted in the isolation of germacrene D (**692**) and the new germacrene, 1(10),5,11-germacatrien-4 α -ol (**701**). The spectroscopic data of **701** were very similar to those of germacrene D (**692**), indicating these two compounds to be structurally related sesquiterpenes. The positions and relative configurations of the α -hydroxy group at C-4, the tertiary methyl at C-4, the vinyl methyl at C-7 and as well as an isopropenyl group at C-7 were confirmed from the 2D-NMR spectra obtained. While a similar compound, 1(10),5-germacradien-4 α -ol (**701a**), was isolated from *Marchantia plicata*, *Conocephalum conicum*, and *Porella swartziana* (40), the NMR data of this compound were not identical with those of **701**. Careful analysis of the 2D-NMR spectra of compound **701a** indicated that its structure should be changed from **701a** to the C-4 epimer, 1(10),5-germacradien-4 β -ol (**702**) (179). The German *Conocephalum conicum* and the Japanese *Wiesnerella denudata* and *Dumortiera hirsuta* elaborate 1(10),5-germacradien-4 β -ol (**702**), which has been isolated also from the Japanese *C. conicum* (492). GC/MS analysis of the volatile component of an unidentified *Jungermannia* species was used to identify 1(10),4-germacradien-6 α -ol (**703**) (494).

In addition to many africanes, the Colombian *Porella swartziana* produced germacraswartzianin (**704**), along with two known germacrenes, germacra-1(10),5-dien-4 β -ol (**702**) and lepidozen-5-ol (**309**) (848). The structure of **704** was not deduced from its 2D-NMR spectra since many signals overlapped, with conclusive evidence for this structure obtained by X-ray crystallographic analysis. The dichloromethane extract of the Portuguese liverwort *Targionia lorbeeriana* was fractionated by flash chromatography to give two germacranolides, 8,15-acetylsalonenolide (= 15-acetoxytulipinolide) (**705**) and 8-acetylsalonenolide (= 15-hydroxytulipinolide) (**706**), together with three guaianolides (see Sect. 4.2.30). Their structures were elucidated by comparison with the NMR data of costunolide (**709**) and by analysis of 2D-NMR data (620).



Germacrane-type sesquiterpenoids found in the Marchantiophyta

The methanol extract of the Indian *Frullania inflata* was fractionated to give (8*S*,13*R*)-8 β -acetoxydihydroparthenolide (**707**) (893), which was isolated from the higher plant, *Liriodendron tulipifera* (Magnoliaceae) (198). Fractionation of the ether extract of the Ecuadorian *Frullania convoluta* resulted in isolation of a new germacranolide, *epi*-isocostunolide (**708**), along with (-)- α -cyclocostunolide (**653**) and (-)-dihydro- α -cyclocostunolide (**655**), (+)-brothenolide (**661**), (+)-nepalensolide A (**662**), and (+)-nepalensolide B (**663**). The similarity of its spectroscopic data to those of costunolide and its 7-epimer with a 6,7-*cis*-lactone ring indicated that **708** is a germacrene-type sesquiterpene lactone. The double bond (*E*) and (*Z*)-configurations and the *cis*-configuration of the lactone ring of **708** were confirmed from its NOESY spectrum (226).

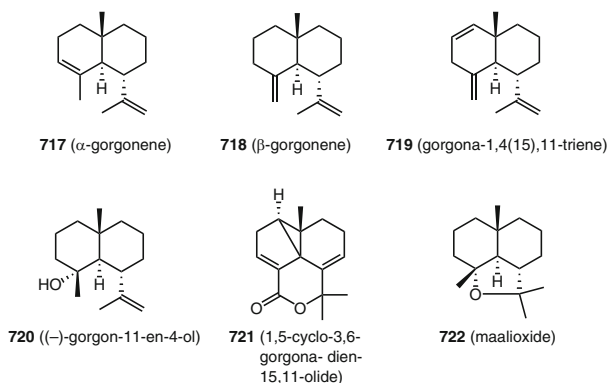
While *Conocephalum japonicum* produces both costunolide (**709**) and its dihydro derivative (**711**), *C. conicum* does not contain either of these germacranolides (493). The methanol extract of *Frullania niqualensis* (410) and an unidentified Tahitian *Frullania* species (424, 426) afforded costunolide (**709**). The presence of tulipinolide (**712**) (= 8 α -acetoxycostunolide) has been confirmed

in *Frullania serrata* (490), and an unidentified Tahitian *Frullania* species (424, 426), and *Wiesnerella denudata* (490, 893).

The Japanese *Porella acutifolia* subsp. *tosana* (315, 316) and *P. perrottetiana* (426) elaborate 4 α ,5 β -epoxy-8-*epi*-inunolide (714). *P. acutifolia* subsp. *tosana* produces the hot-tasting hydroperoxides, 1 α -hydroperoxy-4 α ,5 β -epoxygermacra-10(14),11(13)-dien-12,8 α -olide (715) and 1 β -hydroperoxy-4 α ,5 β -epoxygermacra-10(14),11(13)-dien-12,8 α -olide (716), which have been found also in higher plants (40). *Artemisia fragrans* produces the similar 1 β -hydroperoxy-9 β -acetoxy-11(13)-dihydrogermacra-4,10(14)-diene (716a) (504).

4.2.29 Gorgonanes

A reinvestigation of the essential oil of *Saccogyna viticulosa* resulted in the isolation of α -gorgonene (717), β -gorgonene (718), gorgona-1,4(15),11-triene (719), and gorgon-11-en-4-ol (720). Compound (717) was found to be a double bond isomer of 718. Its structure was elucidated by spectroscopic data comparison with those of 718 and the formation of 717 from β -gorgonene (718) with acid treatment. The structure of gorgonene 719 was assigned as the C-1/C-2 dehydro compound of β -gorgonene (718) by 2D-NMR spectroscopy and its absolute configuration was characterized by enantioselective GC of the reaction products 650, 651, and 722, obtained by rearrangement and dehydration (276).



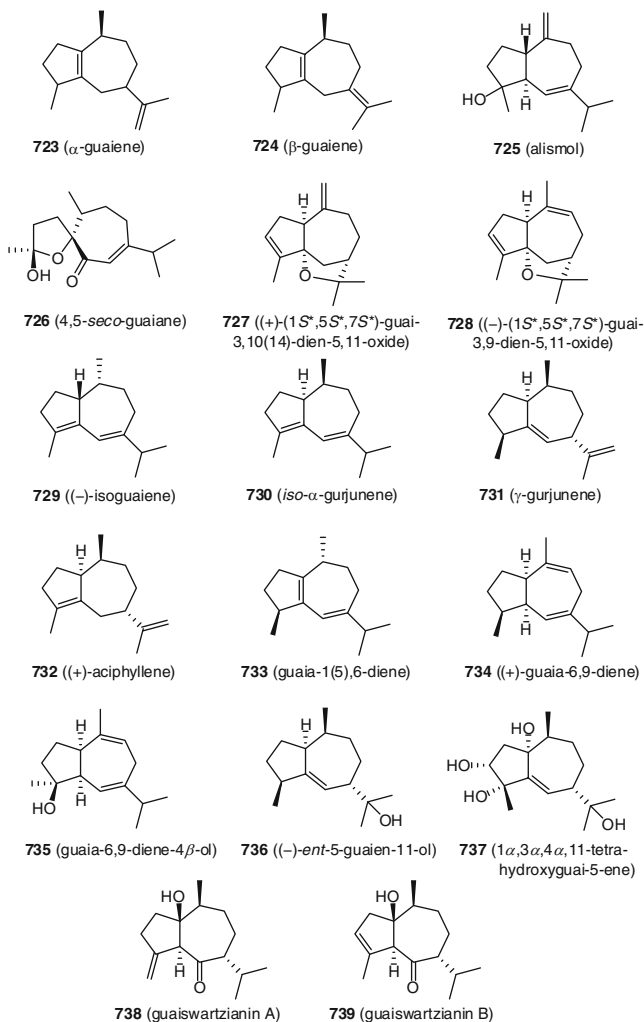
Gorgonane-type sesquiterpenoids found in the Marchantiophyta

The New Zealand *Lepidozia spinosissima* elaborates the cyclogorgonane sesquiterpenoid 721. The relative structure was deduced mainly from its 2D- NMR spectra and the formation of a monoacetate by reduction of 721 with LiAlH_4 , followed by acetylation (611). This is the first record of the isolation of a cyclogorgonane sesquiterpenoid in the Marchantiophyta. The reinvestigation of

the essential oils of *Saccogyna viticulosa* and *Lophozia ventricosa* resulted in the identification of (–)-maalioxide (**722**) (276, 486).

4.2.30 Guaianes

Guaiane sesquiterpenoids are relatively widespread in the liverworts. The simple hydrocarbons, α - (**723**) and β -guaiene (**724**), have been found among the volatile components of several stem-leafy liverworts (40, 45). A guaiane sesquiterpenoid, alismol (= 1 β ,5 α -guaia-6,10(15)-dien-4-ol) (**725**), was isolated by preparative GC from the essential oil of *Preissia quadrata* as the racemate (433).



Guaiane-type sesquiterpenoids found in the Marchantiophyta

The ether extract of the European *Pellia epiphylla* was purified by CC and HPLC to yield *iso*- α -gurjunene B (**730**) and a new 4,5-*seco*-guaiane **726** ([176](#)). The essential oil of *Mylia taylorii* contained two guaiane sesquiterpenoids, guai-3,10 (14)-dien-5,11-oxide (**727**) and its isomer, guai-3,9-dien-5,11-oxide (**728**), as minor constituents, with their structures based on interpretation of the 2D-NMR spectra, including HMBC and NOE. The relative configurations of **727** and **728** were confirmed by the formation of the same dihydro- and tetrahydro derivatives by Pd-catalyzed hydrogenation of **727** and **728** ([922](#)).

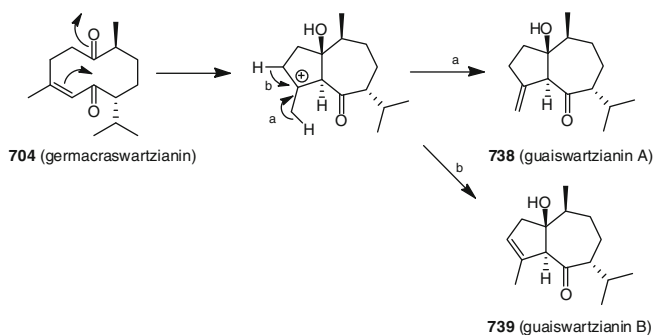
Dumortiera hirsuta was hydrodistilled to obtain an essential oil, which was purified by preparative GC to obtain *ent*-(-)-isoguaiene (**729**). The essential oil was also analyzed by capillary column chromatography on a cyclodextrin phase to identify α -guaiene (**723**), for which the (+)- and (-)-enantiomeric ratio was 84:16%. Aciphyllene (**732**) showed 100% *ee* as the (+)-compound. (+)-Guaia-6,9-diene (**734**) was present also in 100% *ee* ([707](#)), and this same compound was identified in *Drepanolejeunea madagascariensis* ([247](#)). Guaia-1(5),6-diene (**733**) was found only in *Calypogeia muelleriana* ([933](#)).

Further investigation of the essential oil of *Lophozia ventricosa* resulted in the identification of guaia-6,9-dien-4 β -ol (**735**) as a trace constituent ([486](#)). The volatile components of *Lepidozia borneensis* collected in Borneo ([490](#)) and the Indonesian *Dumortiera hirsuta* ([424](#), [426](#)) were investigated to identify this same compound.

The essential oil obtained by hydrodistillation or as a methylene dichloride extract of the German *Calypogeia muelleriana* was analyzed by enantioselective GC-MS and purified by preparative GC, to give (-)-5-guaien-11-ol (**736**), which had not been reported in the literature before ([933](#)). The same compound was isolated from *Conocephalum conicum* ([544](#)) and *Jackiella javanica* ([614](#)).

Heteroscyphus coalitus produced not only aromadendrane (**174**, **175**) and maaliane (**798**), but also a guaiane sesquiterpene alcohol, for which the relative stereostructure was assigned as 1 α ,3 α ,4 α ,11-tetrahydroxyguai-5-ene (**737**) by a combination of 1D- and 2D-NMR experiments (COSY, HMBC, NOESY) ([617](#)).

The Colombian *Porella swartziana* produces not only many africane sesquiterpenoids, but also a few germacrane and guaiane sesquiterpenoids. Guaiaswartzianins A (**738**) and B (**739**) were newly isolated from the ether extract, and the structures of both these compounds were fully elucidated by 2D-NMR methods, inclusive of analysis of their NOESY spectra. Compounds **738** and **739** were inferred as being derived biogenetically from germacraswartzianin (**704**), co-occurring in the same liverwort, by cyclization, as shown in Scheme 4.15 ([848](#)). *Wiesnerella denudata* (Fig. 4.13) is a rich source of germacranolides and guaianolides, like costunolide (**709**) and tulipinolide (**712**). Two samples collected

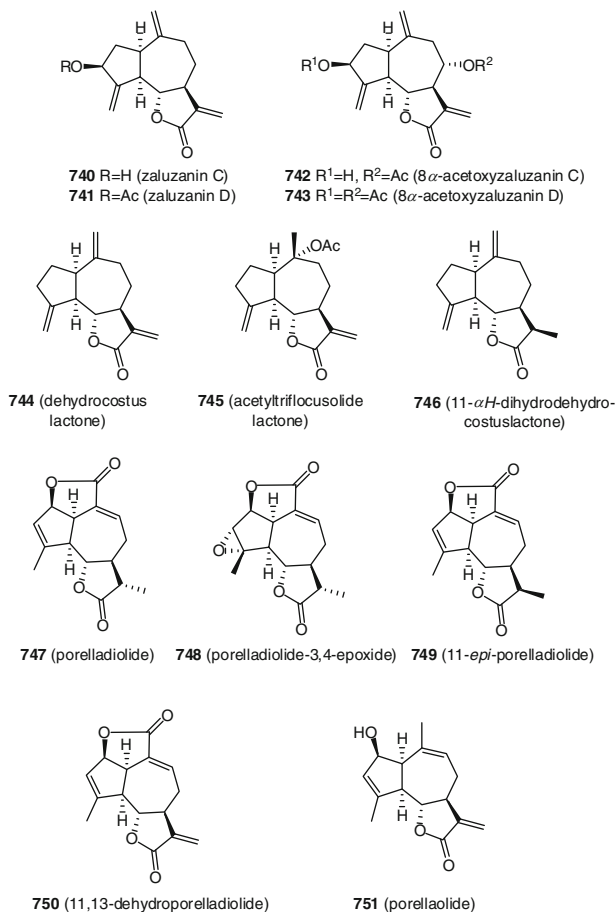


Scheme 4.15 Formation of guaiswartzianins from germacraswartzianin



Fig. 4.13 *Wiesnerella denudata*

from different locations were fractionated to give only tulipinolide (**712**) and costunolide (**709**) from one specimen, with the other producing 8α -acetoxyzaluzanin D (**743**), 8α -acetoxyzaluzanin C (**742**), and zaluzanin C (**740**) ([893](#)). Further fractionation of the ether extract of *W. denudata* led to the isolation of zaluzanin D (**741**) and dehydrocostus lactone (**744**) along with lactones **740**, **742**, and **743** ([84](#)).



Guaiane-type sesquiterpenoids found in the Marchantiophyta

The dichloromethane extract of the Portuguese liverwort *Targionia lorbeeriana* was fractionated by flash chromatography to afford the three guaianolides, dehydrocostus lactone (**744**), acetyltriflocoside lactone (**745**), and 11 α H-dihydrodehydrocostus lactone (**746**). Their structures were characterized using a combination of their 2D-NMR spectroscopic data and X-ray crystallographic analysis of **745** (620). Further investigation of the ether extract of *Porella japonica* led to isolation of the three new guaianolides, 11-*epi*-porelladiolide (**749**), its dehydro derivative, 11,13-dehydroporelladiolide (**750**), and porellaolide (**751**), together with porelladiolide (**747**) and its epoxide **748** (316).

4.2.31 Himachalanes

Several liverworts contain α - (**752**), β - (**753**), and γ -himachalenes (**754**), of which **752** is widespread in species of the Jungermanniales (Table 4.2). *Bazzania japonica*

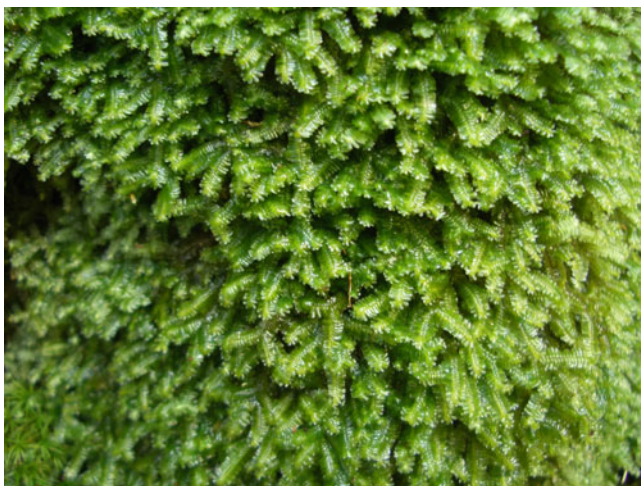
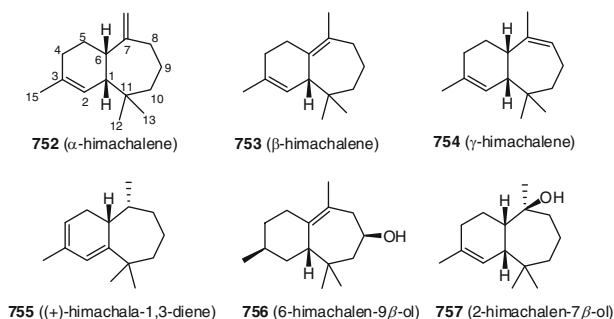


Fig. 4.14 *Bazzania japonica*

(Fig. 4.14) produces himachala-1,3-diene (**755**), representing its first isolation from a liverwort ([485](#)). The same compound was found in the conifer *Abies alba* ([405](#), [406](#)). 6-Himachalen-9 β -ol (**756**) and 2-himachalene-7 β -ol (**757**) were isolated from *Pellia epiphylla* ([176](#)) and *Scapania undulata*, respectively ([16](#)).

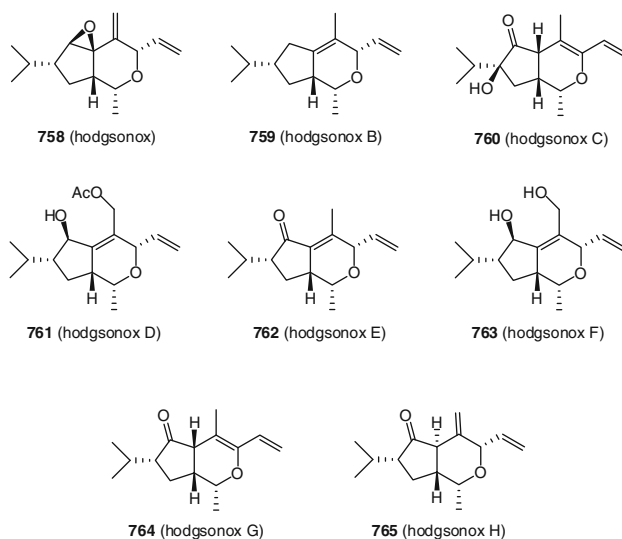


Himalachanes found in the Marchanthophyta

4.2.32 *Hodgsonoxanes*

A sesquiterpene based on a new carbon skeleton named hodgeonox (**758**) was isolated from the New Zealand *Lepidolaena hodgeonae*. This compound was established with a cyclopenta[5.1-*c*]pyran ring structure having a doubly allylic ether functionality, from the analysis of NMR spectroscopic data of both **758** and its diepoxide prepared with *m*CPBA, and application of molecular modeling (MM2 force field) for the parent compound ([22](#)).

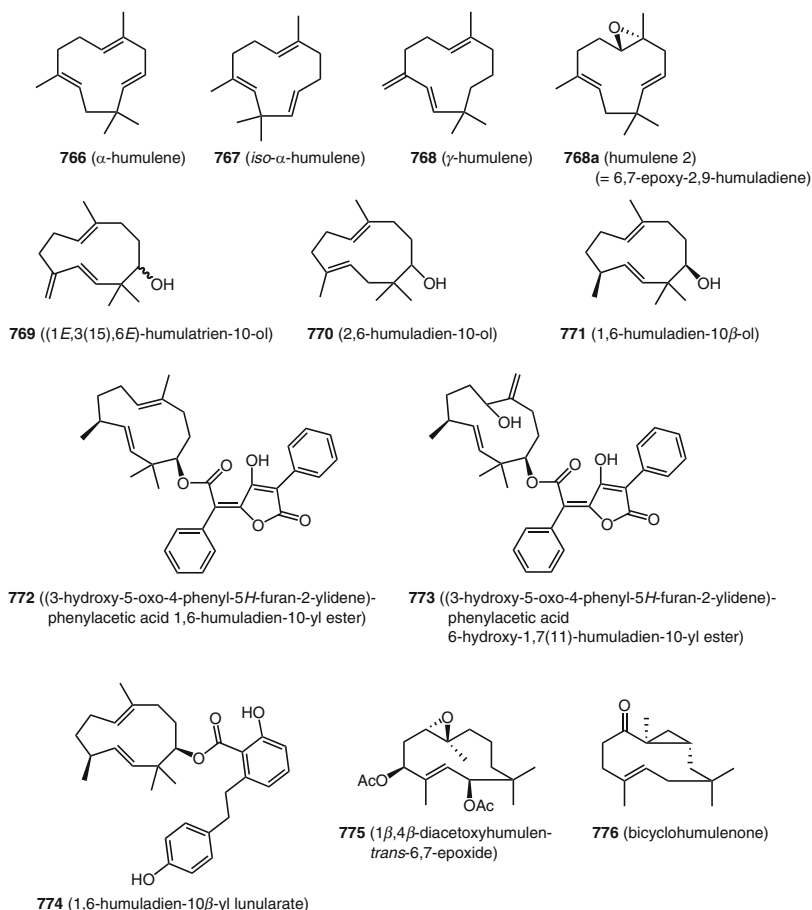
A biosynthesis study on hodgeonox (**758**) in *Lepidolaena hodgeonae* was carried out by Barlow and associates, using [1-¹³C] labeled glucose in axenic cultures of this liverwort. Quantitative ¹³C NMR stereoscopic analysis demonstrated that the isoprene units are derived from the methylerythritol phosphate (MEP) pathway (100). Further fractionation of *L. hodgeonae* resulted in the isolation of seven new hodgeonoxane sesquiterpenoids, hodgeonox B (**759**), hodgeonox C (**760**), hodgeonox D (**761**), hodgeonox E (**762**), hodgeonox F (**763**), hodgeonox G (**764**), and hodgeonox H (**765**), together with a large amount of hodgeonox (**758**). All structures were characterized mainly from their 2D-NMR spectroscopic data. These seven sesquiterpenoids were found to be new compounds with the same substituted cyclopentapyran skeleton as hodgeonox (**758**). Compounds **764** and **765** were isolated only from a stored sample of the dried plant and were suggested as being artifacts (101).



Hodgeonoxane-type sesquiterpenoids found in the Marchantiophyta

4.2.33 Humulanes

Eleven humulanes have been found in the liverworts. α -Humulane (**766**) is the most widespread in Jungermanniales species, but also occurs in *Aneura alterniloba* (72). The reinvestigation of the essential oil of *Saccogyna viticulosa* resulted in the isolation of *iso*- α -humulene (**767**), for which the structure was assigned by a combination of COSY, HMBC, and NOESY NMR experiments. The (*E*)-configuration of the C-10/C-11 double bond was deduced from the coupling constant of 15.8 Hz at δ_{H} 5.48 ppm for H-11 (276). γ -Humulene (**768**) has been found only in *Bazzania trilobata* previously (930).



Humulane-type sesquiterpenoids found in the Marchantiophyta

The ether extract of the Costa Rican *Bryopteris filicina* contained the humulane sesquiterpenoid **769**, which was not detected in the same species collected in Panama (576). A combination of the ^1H and ^{13}C NMR spectroscopy with 2D-NMR (COSY, HMBC, and NOESY) methods indicated that the structure of **769** is (1*E*,3(15),6*E*)-humulatrien-10-ol, with the configuration at C-7 not determined (604).

The ether extract of the sporophytes of *Pellia epiphylla* was purified by CC to give 2,6-humuladien-10-ol (**770**). The same compound was also isolated from a dichloromethane extract of the spores of *P. epiphylla*. The monocyclic skeleton of **770** was proposed by its MS, ^{13}C NMR, and DEPT spectra, with the complete structure deduced using COSY, HMBC, and NOESY experiments (175).

The ether extract of the New Zealand *Tylimanthus tenellus* gave three new humulane sesquiterpenoids, (–)-1,6-humuladien-10 β -ol (**771**), (+)-1,6-humuladien-10-yl-(3-hydroxy-5-oxo-4-phenyl-5*H*-furan-2-ylidene)-phenyl acetate (**772**), and (–)-6-hydroxy-1,7(14)-humuladien-10-yl-(3-hydroxy-5-oxo-4-phenyl-5*H*-furan-2-ylidene)-phenyl acetate (**773**). The absolute configuration of **772** was

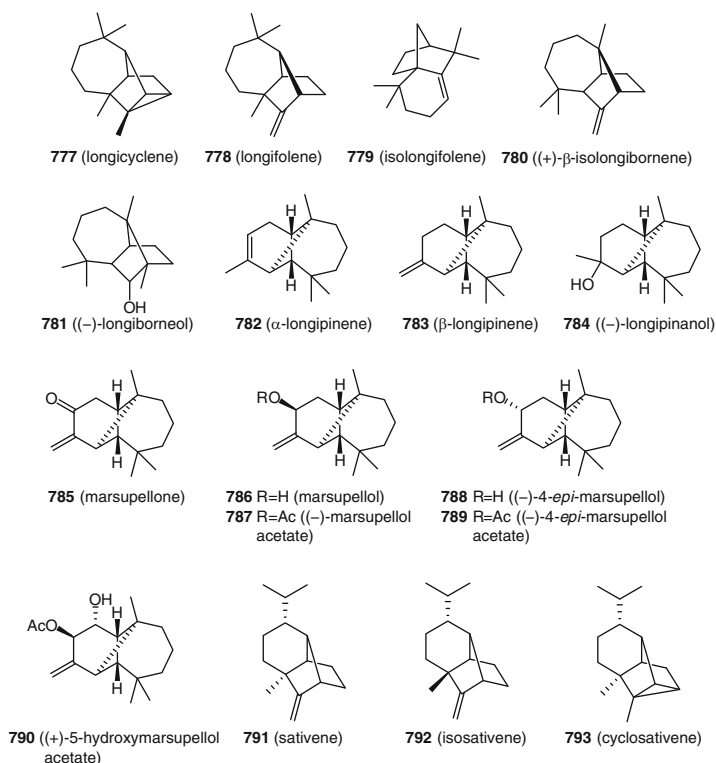
established by a combination of 2D-NMR spectroscopy and X-ray crystallographic analysis and the modified *Mosher* method. The structure of **772** was investigated further by spectroscopic and optical rotation data comparison with humuladiene, obtained by hydrolysis of **772**, and a lanthanide- induced shift (LIS) experiment of the (+)-(*R*)- and (–)-(*S*)-MTPA esters of compound **772** (896). The same compound was isolated from the thalloid liverworts, *Marchantia emarginata* subsp. *tosana* (347) and *Conocephalum japonicum* (84). The structure of **773** was mainly based on the comparison of its 2D-NMR spectroscopic data with those of **772**. To establish the configuration of C-6, a conformational analysis of **773** was carried out for an optimized structure by means of the Molecular Operating Environment (MOE) software program with Merck molecular force field 94 (MMFF 94) parameters. Unfortunately, for many optimized conformers the differences in the formation energies were within 42 KJ/mol. Thus, it was difficult to compare the result of an NOE experiment with that of the above-mentioned conformational analysis (896).

The hydrodistilled oil of the Taiwanese *Bazzania tridens* was purified by CC to give a norhumulene **775**, for which the gross structure was assigned as 1 β ,4 β -diacetoxylumulen-*trans*-6,7-epoxide by 2D-NMR procedures (959). The ether extract of *Plagiochila sciophila* was reinvestigated by GC/MS to identify bicyclohumulenone (**776**) as one of the major components (492). Bioactivity-guided fractionation of the ether extract of *Plagiochila ovalifolia*, using assays for DPPH radical-scavenging and germination stimulation for dormant lettuce seeds, resulted in the isolation of bicyclohumulenone (**776**) (701).

The *n*-hexane extract of *Marchantia emarginata* subsp. *tosana* afforded a new humulane sesquiterpene ester, **774**, together with (+)-1,6-humuladien-10 β -ol (**771**). The structure of **774** was determined as (–)-1,6-humuladien-10 β -yl lunularate by a combination of ¹H- and ¹³C NMR spectroscopy, which showed the presence of 1,6-humuladien-10 β -ol (**771**) and lunularic acid (**1478**) moieties. The connectivity of both groups at C-10 was confirmed by the presence of an ester carbonyl group (IR: 1720 cm^{–1}) and a fragment peak at *m/z* 258 in the mass spectrum, originating by a *McLafferty* rearrangement, and by analysis of 2D-NMR spectroscopic data (COSY, HMBC, HMQC, NOESY) (347).

4.2.34 Longifolanes, Longibornanes, Longipinanes, and Longicyclanes

Longifolene (**778**) is distributed mainly among species of the Jungermanniales. However, longicyclene (**777**), isolongifolene (**778**), and β -isolongifolene (**779**) have been found only in a more restricted group of taxa (Table 4.2).



Longicyclene, longifolane-, longibornane, longipinane, and sativane-type sesquiterpenoids found in the Marchantiophyta

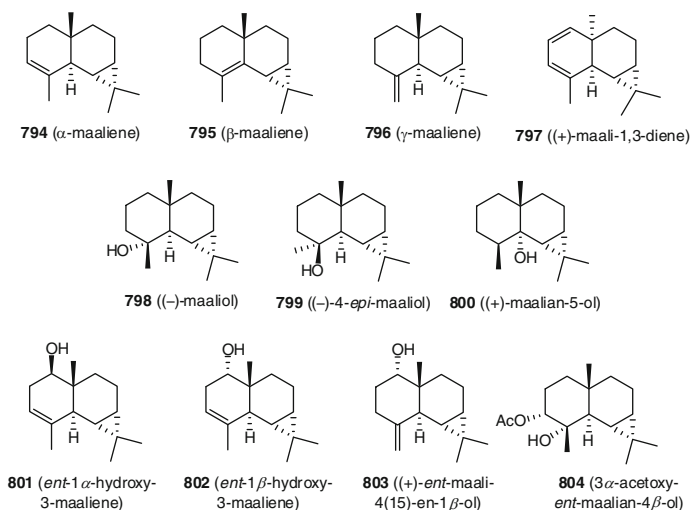
The German *Scapania undulata* biosynthesizes (+)-β-isolongibornene (**780**) (16), for which the spectroscopic data proved to be identical with those of an unidentified sesquiterpene hydrocarbon, scapanene, isolated from *S. undulata* (28, 39). The structure of **780** was found to resemble those of β-longipinene (**783**) and longiborneol (**781**), which are the major components of *S. undulata*. Compound **780** was found in the ether extract of the Tahitian *Mastigophora diclados* (425, 494). (–)-Longiborneol (**781**) and (–)-longipinanol (**784**) have been isolated from the ether extract of the Japanese *Scapania undulata* along with five new labdanes (see Sect. 4.3.8) (973). In addition, longicyclene (**777**), longifolene (**778**), α-longipinene (**782**), β-longipinene (**783**), (–)-longipinanol (**784**), α-ylangnene (**457**), sativene (**791**), and many other sesquiterpene hydrocarbons could be characterized (16). Compound **782** has been also isolated from the essential oil of *Plagiochila bifaria* (277).

Bioactivity-guided fractionation of the ether extract of an unidentified Tahitian *Plagiochila* species using the DPPH radical-scavenging assay resulted in the isolation of β-longipinene (**783**) (701). The Argentinian *Plagiochasma rupestre* produces β-longipinene (**783**) and marsupellone (**785**) (97). *Marsupella emarginata* is a rich source of longipinane sesquiterpenoids (40). Further investigation of the secondary metabolites of the same species led to the previously isolated

marcupellol (**786**), marsupellol acetate (**787**), and the three additional longipinanes, 4-*epi*-marsupellol (**788**), its acetate (**789**) and 5-hydroxymarsupellol acetate (**790**) (**17**). The essential oil of the Taiwanese *Lepidozia fauriana* was analyzed by GC/MS to detect isosativene (**792**) (**645**). *Dumortiera hirsuta* was hydrodistilled to obtain an essential oil, which was analyzed by capillary column chromatography on a cyclodextrin derivative to identify (–)-cyclosativene (**793**), with an *ee* of 100% (**707**).

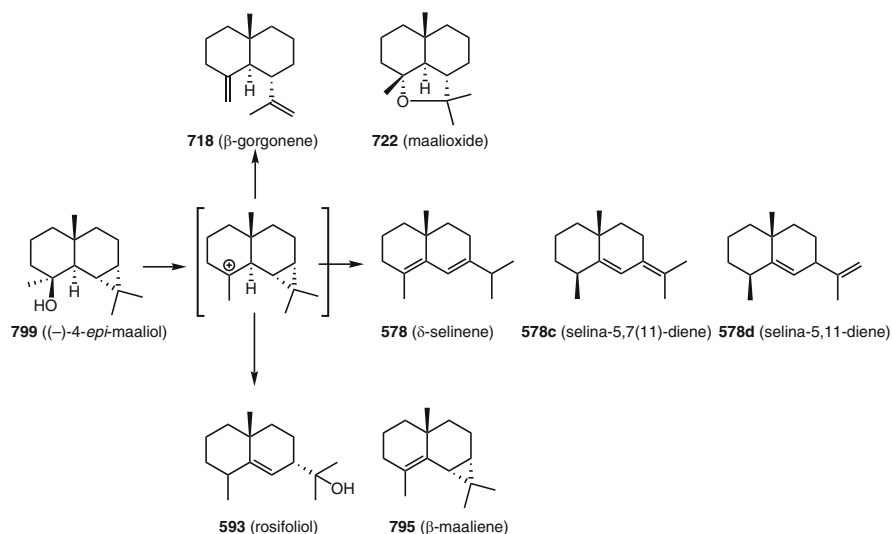
4.2.35 Maalianes

In the liverworts, β- (**795**) and γ-maaliene (**796**), together with maaliol (**798**), (+)-maalian-5-ol (**800**), and (+)-*ent*-maali-4(15)-en-1β-ol (**803**) are known to occur (**39**, **40**). α-Maaliene (**794**) was isolated for the first time in the liverworts *Calypogeia muelleriana* (**933**) and *Plagiochila asplenioides* (**14**, **604**).



Maaliene-type sesquiterpenoids found in the Marchantiophyta

The ether extract of the European *Plagiochila asplenioides* was further investigated to afford two maalianes, (–)-γ-maaliene (**796**) and maalian-5-ol (**800**), which have already been found in *Riccardia chamedryfolia* and *Plagiochila ovalifolia* (**40**). The essential oil obtained by hydrodistillation or from the methylene dichloride extract of the German *Calypogeia muelleriana* was analyzed by enantioselective GC/MS, and 47 compounds were identified. The major component, maali-1,3-diene (**797**), was isolated by preparative GC. A combination of their spectroscopic data and analysis of the hydrogenated products by GC indicated the stereochemistry of C-10 to be different from that of the hydrogenated products of γ-maaliene (**796**), indicating the orientations of the C-10 methyl groups of **797** and **796** as being opposite to one another (**933**). (–)-γ-Maaliene (**796**) has also been found in an unidentified *Pallavicinia* species collected in Borneo (**490**).



Scheme 4.16 Reaction of (–)-4-*epi*-maaliol with Amberlyst[®] resin

(–)-Maaliol (**798**) was isolated from the ether extract of the Colombian *Plagiochila cristata* (**911**), the Japanese *Heteroscyphus coalitus* (**617**), and *Porella ovalifolia* (**84**), in addition to the essential oil of *Lophozia ventricosa* (**486**).

The essential oil of *Plagiochila asplenioides* was purified by preparative GC to obtain (–)-4-*epi*-maaliol (**799**), for which the stereostructure determined was based on 2D-NMR (COSY, HMBC, HMQC, NOESY) methods. Its absolute configuration was established by treatment of **799** with Amberlyst[®] resin to give β -maaliene (**795**), β -gorgonene (**718**), selina-5,11-diene (**578d**), (+)- δ -selinene (**578**), maaliolide (**722**), selina-5,7-diene (**578c**), and a trace of rosifoliol (**593**). The identification of compound **578** was proved by comparison with an authentic reference compound by enantioselective GC (Scheme 4.16). The (+)-enantiomer of **799** was isolated from Brazilian Vassoura oil and its relative configuration was elucidated using COSY and NOESY NMR spectroscopy by Weyerstahl and associates (**939**).

The essential oil of *Plagiochila asplenioides* was also analyzed by GC/MS to identify maali-1,3-diene (**797**) (**14**). Bioactivity-guided fractionation of the ether extract of *Plagiochila ovalifolia* using the DPPH radical-scavenging assay resulted in the isolation of maalian-5-ol (**800**) (**701**). (1*R*,5*R*,6*S*,7*S*,10*R*)-1-Hydroxy-3-maaliene (= *ent*-1 α -hydroxy-3-maaliene) (**801**) was isolated from *Leptoscyphus jackii* together with (–)-bicyclogermacrene (**293**). The absolute configuration of **801** was established by the negative Cotton effect of 1-oxomaaliene-4(15)-ene prepared from **801** using the PCC reagent (**893**).

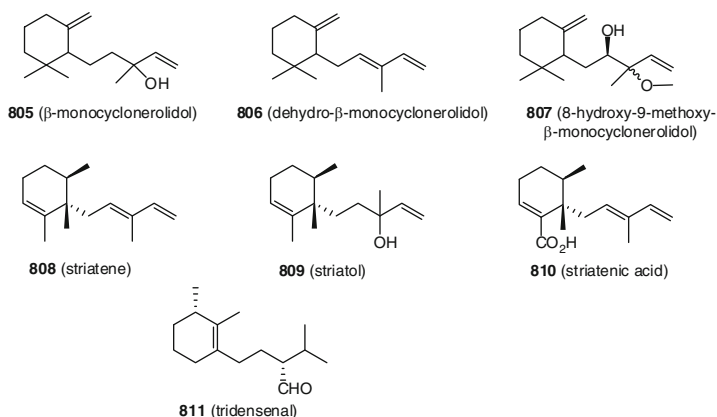
Fractionation of the ether extract of the New Zealand *Chiloscyphus mittenianus* (**347**) and an unidentified New Zealand *Heteroscyphus* species (**635**) led to the isolation of a new maaliene sesquiterpene alcohol (**802**), for which the structure was elucidated as *ent*-1 β -hydroxy-3-maaliene from its COSY, HMQC, HMBC,

and NOESY spectra. The absolute configuration of this substance remained to be elucidated (347). The C-1 epimer (**801**) was isolated from *Leptoscyphus* species (893).

The European *Mylia taylorii* produces (+)-*ent*-maali-4(15)-*en*-1 β -ol (**803**) (569). The same compound has been found in *Kurzia trichoclados* and two *Mylia* species (922). The New Zealand *Lepidozia spinossima* contains the new oxygenated maaliane sesquiterpenoid **804**. Its relative configuration was determined by a combination of 1D- and 2D-NMR spectroscopic methods (HMBC, NOESY). Reduction of **804** gave a diol in low yield because of an axial acetate group at C-3 of **804**. The CD spectrum of **804** in Eu(fod)₃ showed a negative and a positive Cotton effect at 322 and 272 nm, indicating that **804** possesses the (*R*)- and (*S*)-configuration at C-3 and C-4. Thus, the absolute structure of **804** was established as (–)-3 α -acetoxy-*ent*-maalian-4 β -ol (611, 616).

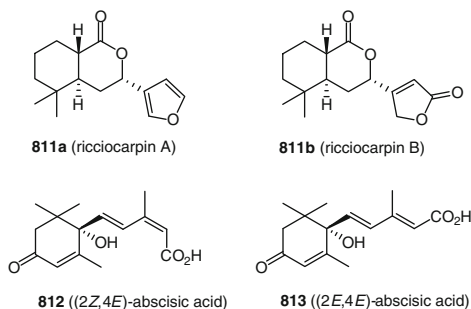
4.2.36 Monocyclofarnesanes

The ether extract of *Archilejeunea olivacea* was purified by CC on silica gel and by subsequent HPLC to give β -monocyclonerolidol (**805**), the putative precursor for a trinorsesquiterpene hydrocarbon, olivacene (927) (879). Dehydro- β -monocyclonerolidol (**806**) and 8-hydroxy-9-methoxy- β -monocyclonerolidol (**807**) were isolated from the ether extract of *Porella subobtusa*. The 2D-NMR data confirmed that **806** is a dehydro- β -monocyclofarnesane-type sesquiterpenoid. The similar β -monocyclonerolidol (**805**) has been isolated from the liverwort *Ptychanthus striatus* (40). Thus, compound **806** is the dehydro derivative of **805**. Comparison of the NMR data of **807** with those of **806** suggested that the structure of **807** is a monocyclofarnesane-type with a secondary alcohol at C-8 and a methoxy group at C-9. The absolute (*R*)-configuration at C-8 was confirmed by the modified Mosher method. Thus, the structure of **807** was assigned as (8*R*)-hydroxy-9 ξ -methoxy- β -monocyclonerolidol (**807**) (581).



Monocyclofarnesane-type sesquiterpenoids found in the Marchantiophyta

Compound **806** was identified in the ether extract of *Porella perrottetiana* (424). Striatene (**808**) and striatol (**809**) have been found in several liverworts (40). Hashimoto and associates, and Wu and coworkers, reinvestigated Japanese and Taiwanese samples of *Ptychanthus striatus* chemically to isolate striatene (**808**) and striatol (**809**) (320, 957). Further investigation of the essential oil of *Lophozia ventricosa* resulted in the identification of striatol (**809**) in trace amounts (486).



Monocyclofarnesane-type sesquiterpenoids found in the Marchantiophyta

The total synthesis, using (*R*)-pulegone as a starting material, of natural (+)-striatene (**808**) isolated from *Ptychanthus striatus*, was achieved by Bremond and associates in 71% yield and more than 95% *ee*. The enantiomeric (–)-striatene can also be prepared from (*S*)-pulegone (129). A biosynthetic study of striatol (**809**) was carried out by Katoh et al. Potassium [2-¹³C]- and [4,4-²H₂]-mevalonate were fed into the suspended culture cells of *Ptychanthus striatus* and the labeled striatol (**809**) could be isolated. The ²H and ¹³C NMR studies conducted showed proton cyclization between the distal and central double bond in farnesyl pyrophosphate and a concerted series of 1,2-migrations of a hydrogen and a methyl group, with subsequent elimination of a proton (396). A concerted series of 1,2-migration of a hydrogen and a methyl group coupled with proton elimination has been postulated to be involved in the biosynthesis of pinguianes, such as 6α-hydroxy-3-oxopinguin-5(10)-ene-11,6-olide (**879**) (812, 813). Thus, the striatanes and pinguianes might be formed from a common intermediate.

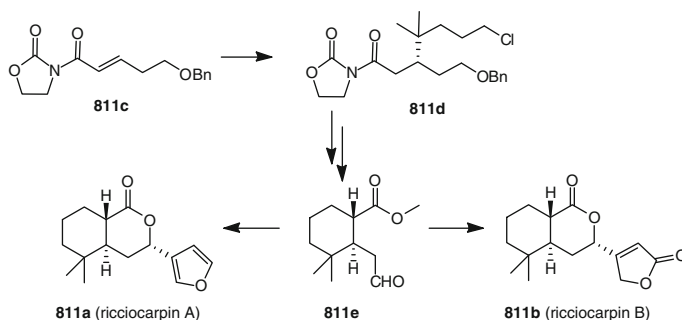
From the ether extract of the Malaysian *Cheilolejeunea serpentina* a new monocyclofarnesane sesquiterpenoid, striatenic acid (**810**), was isolated and its structure including the absolute configuration established by an extensive 2D-NMR data analysis, and by the total synthesis of the optically active methyl ester of **810** using (*R*)-pulegone as the starting material (854).

The cultured cells of *Ptychanthus striatus* were fractionated by CC to give striatol (**809**), kelsoene (**915**), and prespatane (**340**) (396, 565). Two monocyclofarnesanes, ricciocarpin A (**811a**) and ricciocarpin B (**811b**), were isolated previously from *Ricciocarpos natans* (40). The concise total synthesis of (±)-ricciocarpin A (**811a**) was accomplished by Agapiou and Krische by highly chemoselective catalytic crossed *Michael* cycloisomerization of thioenoates with appendant aryl ketone and enoate partners, which afforded cyclopentane and cyclohexane products (20).

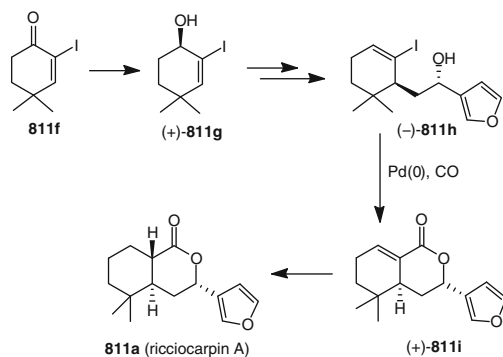
Sibi and *He* have developed an efficient enantioselective total synthesis of ricciocarpins A (**811a**) and B (**811b**) in 41 and 45% overall yields starting from the β -substituted oxazolidinone **811c** (Scheme 4.17) (750). A novel enantioselective total synthesis of (+)-ricciocarpin A (**811a**) was achieved by *Jan* and *Liu*, using 4,4-dimethyl-2-isodo-2-cyclohexenone (**811f**) as the starting material, in 10 steps in 26% overall yield, with high optical purity (98% *ee*) (Scheme 4.18) (375).

Recent studies on the deoxyxylulose phosphate pathway of terpenoid biosynthesis in plants including liverworts and microorganisms were reviewed by *Eisenreich* and associates (201). Bornyl acetate (**58**) in *Conocephalum conicum*, *epi*-neoverucosane in *Fossombronia alaskana* (830), and phytol (**1316**) in *Heteroscyphus planus* are biosynthesized through the deoxyxylulose pathway. On the other hand, ricciocarpin A (**811a**) in *Ricciocarpos natans* and heteroscyphic acid A (**961**) in *Heteroscyphus planus* were produced through the mevalonate pathway (830).

Marchantia polymorpha contains both abscisic acid (ABA) (= (2*Z*,4*E*)-abscisic acid) (**812**) and (2*E*,4*E*)-abscisic acid (**813**) in a 1.2:1 ratio. ABA (**812**) is present in *M. polymorpha* at levels similar to those found in higher plants. Its presence in the



Scheme 4.17 Enantioselective total synthesis of ricciocarpin A



Scheme 4.18 Enantioselective total synthesis of ricciocarpin A

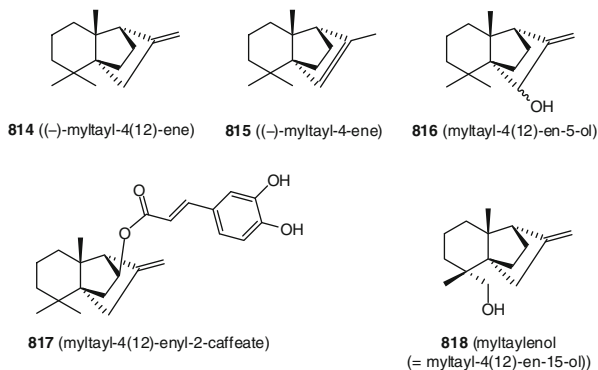
gametophyte of *M. polymorpha* is consistent with the function of ABA as a plant hormone in liverworts. This was the first report of the identification of ABA and its (2*E*)-isomer in the Marchantiophyta (467).

4.2.37 Myltaylanes and Cyclomyltaylanes

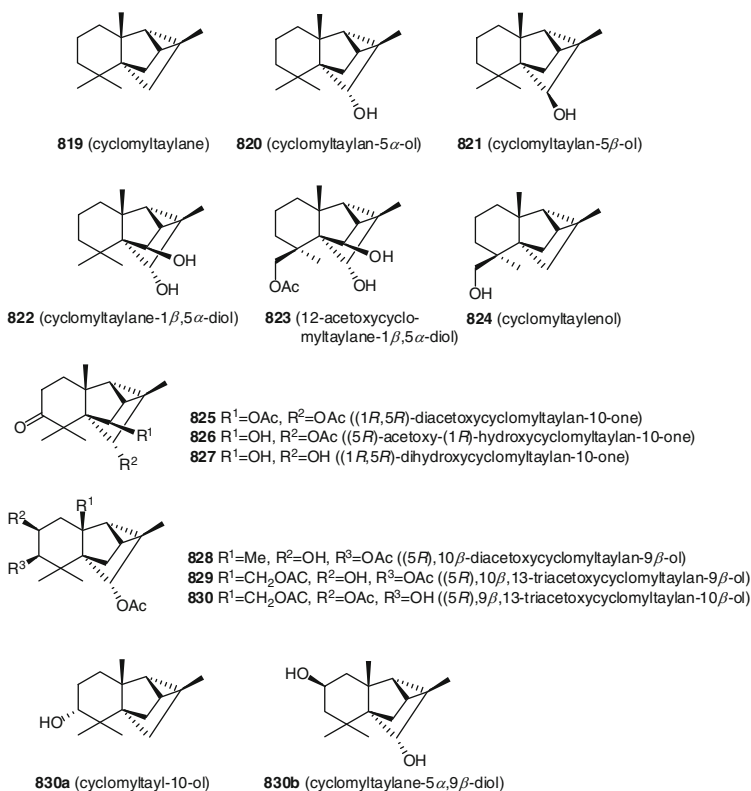
Various myltaylane and cyclomyltaylanes were identified, particularly in *Bazzania*, *Mylia*, and *Reboulia* species (Table 4.2).

The Austrian *Marsupella aquatica* elaborated (–)-myltayl-4(12)-ene (**814**) and cyclomyltaylane (= tridensene) (**819**) together with the three amorphanes, (+)-amorpha-4,11-diene (**370**), (–)-amorpha-4,7(11)-diene (**371**), and (–)-acetoxyamorpha-4,7(11)-diene (**372**), as previously mentioned (17). Further investigation of the essential oil of the same liverwort resulted in the isolation of a new myltaylane hydrocarbon, (–)-myltayl-4-ene (**815**), which is the double bond isomer of (–)-myltayl-4(12)-ene (**814**). Compounds **814**, **815**, and **819** were also detected in *Mylia taylorii* and *Kurzia trichoclados* (922). Additional to the three compounds mentioned above, cyclomyltaylenol (**824**) and maali-4(15)-en-1-ol (**803**) have been found in the essential oils of *Mylia taylorii* and *M. nuda* (922).

A new myltaylane sesquiterpenoid, myltayl-4(12)-en-5-ol (**816**) was isolated from the ether extract of the French *Bazzania trilobata*. The planar structure of **816** was determined using 2D-NMR spectroscopy (582). The stereostructure of **816** was deduced from a comparison with similar myltaylanes and cyclomyltaylanes in other liverworts, for which their absolute configurations had been established by X-ray crystallographic analysis, and from their CD spectra (40). This is the first isolation of such a compound from the Marchantiophyta (582). Myltaylenol (**818**) and cyclomyltaylenol (**824**) have also been isolated from the Austrian *Mylia taylorii* (569).



Myltaylane-type sesquiterpenoids found in the Marchantiophyta



Cyclomyltaylane-type sesquiterpenoids found in the Marchantiophyta

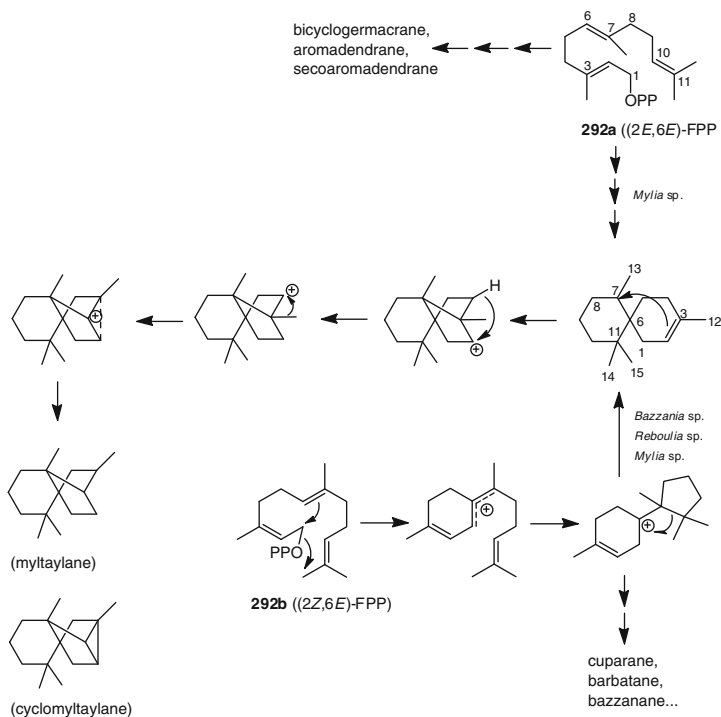
Fractionation of the ether extract of the Madagascan *Bazzania nitida* resulted in the isolation of the new myltaylane ester (**818**), together with the detection of acorane, barbatane, calamenane, chamigrane, isobazzanane, gymnomitrane, and isobazzane sesquiterpenoids. The stereochemistry proposed for **818** was based on a combination of its HMBC and NOESY NMR spectra and comparison with the spectroscopic data with those of known myltaylanes found in other *Bazzania* species (289).

The volatile components of *Plagiochila sciophila* and *Reboulia hemisphaerica* were reinvestigated by GC/MS to identify cyclomyltaylane (**819**) from the former species and **819** and a large amount of cyclomyltaylan-5 α -ol (**820**) from the latter species (492). Wei and associates reported the isolation of **820** from the Taiwanese *R. hemisphaerica* and its structure was elucidated by comparison with the spectroscopic data of cyclomyltaylane (**819**), inclusive of HMBC and NOESY experiments (935). Compound **819** occurred in the same species and has been isolated from *Bazzania tridens* (40). The first enantioselective total synthesis of (+)-cyclomyltaylan-5 α -ol (**820**) was achieved by Sakai and coworkers starting from the optically active (*S*)-(+)-Hajos-Wiechert ketone analogue via SmI₂-prompted reductive coupling as a key step, in ca. 1.2% overall yield over 18 steps (703).

Reboulia hemisphaerica has three chemotypes, the aristolane, cyclomyltaylane, and gymnomitrane-cuparane types. The further fractionation of a species

representing the second of these types led to the isolation of three new cyclomyltaylanes, cyclomyltaylan-5 β -ol (**821**), cyclomyltaylane-1 β ,5 α -diol (**822**), and 12-acetoxycyclomyltaylane-1 β ,5 α -diol (**823**), and the known cyclomyltaylan-5 α -ol (**820**). The relative configuration of **820** was further established by the X-ray crystallographic analysis of its 3,5-dinitrobenzoate. The absolute configuration was also confirmed by application of the modified *Mosher* method for one of the metabolites (**830b**) obtained from the biotransformation of compound **820** by the fungus *Aspergillus niger*. The structures of the other new compounds were based on their X-ray crystallographic analysis (242).

Fractionation of the ether extract of the Madagascan *Bazzania madagassa* led to the isolation of a new cyclomyltaylane sesquiterpenoid, for which the absolute configuration was established as (1*R*,5*R*)-diacetoxycyclomyltaylan-10-one (**825**), by comparison of the *Cotton* effects of the original compound with those of a mono ketone derived from cyclomyltayl-10-ol (**830a**). Myltaylanes and cyclomyltaylanes are very rare sesquiterpenoids found only in liverworts from the genera, *Mylia*, *Bazzania*, *Reboulia*, and *Mannia*. The myltaylane skeleton may be derived from C-3 to C-7 cyclization of β -chamigrene (**436**), followed by migration of the methyl group to the vicinal proton. Taking into account the co-occurrence of β -chamigrene (**436**) in *B. madagassa* as a precursor, the biosynthesis of myltaylane and cyclomyltaylanes in liverworts is suggested as shown in Scheme 4.19 (291).

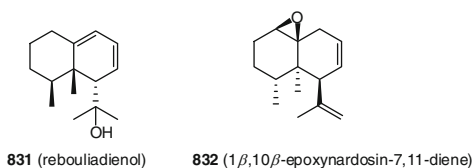


Scheme 4.19 Possible biogenesis pathways of myltaylane- and cyclomyltaylane-type sesquiterpenoids

The Madagascan *Bazzania madagassa* elaborated six new cyclomyltaylane sesquiterpenoids. The absolute configuration of (1*R*,5*R*)-diacetoxycyclomyltaylan-10-one (**825**) was settled by its X-ray crystallographic analysis and from its CD spectrum. The structures of the remaining compounds were established as (5*R*)-acetoxo-(1*R*)-hydroxycyclomyltaylan-10-one (**826**) and (1*R*,5*R*)-dihydroxycyclomyltaylan-10-one (**827**), by interpretation of their 2D-NMR and CD spectra. In turn, HMBC, HMQC and NOE correlation spectra were used to propose the structures of **828**, **829**, and **830** as (5*R*,10*β*)-diacetoxycyclomyltaylan-9*β*-ol, (5*R*,10*β*,13)-triacetoxycyclomyltaylan-9*β*-ol, and (5*R*,9*β*,13)-triacetoxycyclomyltaylan-10*β*-ol (**293**).

4.2.38 *Nardosinanes*

Rebouladienol (**831**) is a nardosinane sesquiterpene, a rare compound class in Nature, and has been isolated from the liverwort *Reboulia hemisphaerica* (**40**, **436**, **889**). It is noteworthy that the dichloromethane extract of the fruiting bodies of the mushroom *Russula lepida* produces the same nardosinane sesquiterpenoid, rulepidanol, for which the absolute configuration was determined as (4*S*,5*S*,6*S*)-nardosina-7,8-dien-11-ol (= rulepidanol) (**831**) by the positive *Cotton* effect for the π - π^* transition of the skewed conjugated diene moiety (**916**). Nardosinane sesquiterpenes are believed to be formed from an aristolane precursor (**687**). The co-occurrence of compound **831** with aristolanes **110–113** in the same liverwort reinforces this hypothesis. The ether extract of *Gackstroemia decipiens* produced 1*β*,10*β*-epoxynardosin-7,11-diene (**832**) (**251**).

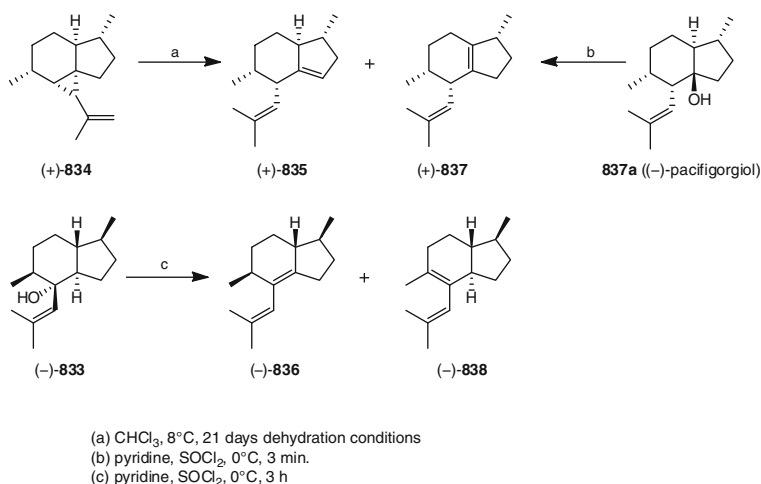


Nardosinane-type sesquiterpenoids found in the Marchantiophyta

4.2.39 *Pacifigorgianes*

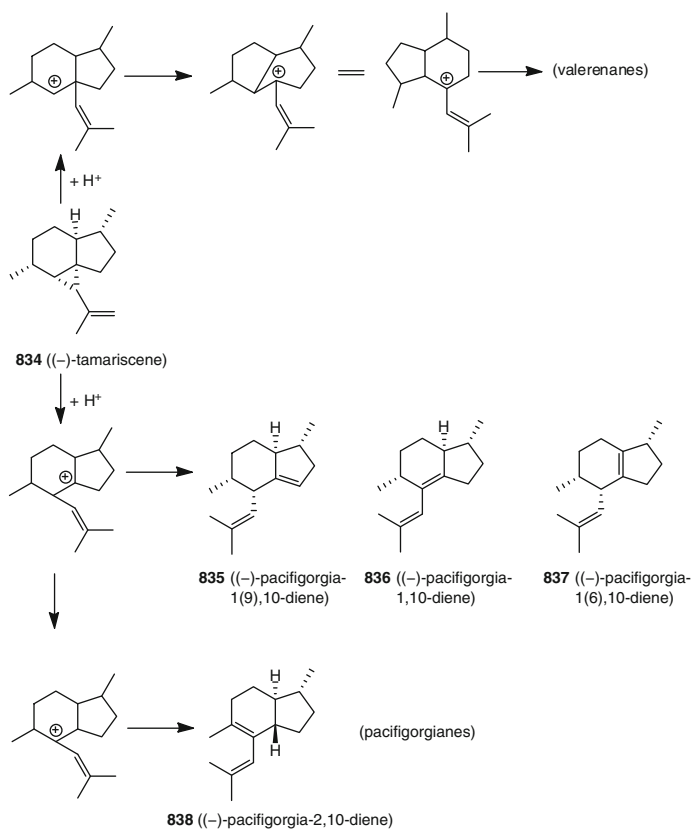
Frullania species contain not only eudesmane and eremophilane sesquiterpene lactones but also the pacifigorgiane sesquiterpenoid, (–)-tamariscol (**833**) (**40**). The sesquiterpenoid constituents of the essential oil obtained by

hydrodistillation of *F. fragilifolia* were purified by HPLC and preparative GC to afford (–)-tamariscene (**834**) as the major component (11% of total essential oil), as well as (–)-pacifigorgia-1(9),10-diene (**835**), (–)-pacifigorgia-1,10-diene (**836**), (–)-pacifigorgia-1(6),10-diene (**837**), (–)-pacifigorgia-2,10-diene (**838**), and (+)-pacifigorgia-2(10),11-diene (**839**), together with bicyclogermacrene, bourbonane, copaane, elemene, germacrene, humulene, and muurolane sesquiterpenoids. Similar work up of the essential oil of *F. tamarisci* afforded compounds **834–837** and **839**, with (–)-tamariscol (**833**), as the major component (56%), along with bazzanene and hydrocarbons of the same sesquiterpene classes as mentioned above. The absolute configurations of the new pacifigorgianes **834–839** were established by a combination of 2D-NMR data interpretation and dehydration of (–)-pacifigorgiol (**837a**) obtained from *Valeriana officinalis* and tamariscol (**833**), as shown in Scheme 4.20, in addition to polarimetric measurements, total hydrogenation, and enantioselective GC using cyclodextrin as stationary phase. It is noteworthy that the higher plant *Valeriana officinalis* also produces (+)-tamariscene (**834**), the enantiomer isolated from *Frullania* species, (+)-(**835**) and (+)-(**837**), as well as (–)-valerena-4,7(11)-diene (**935**). The co-occurrence of both pacifigorgianes and valerenanes in *V. officinalis* and both enantiomers of tamariscene (**834**) in

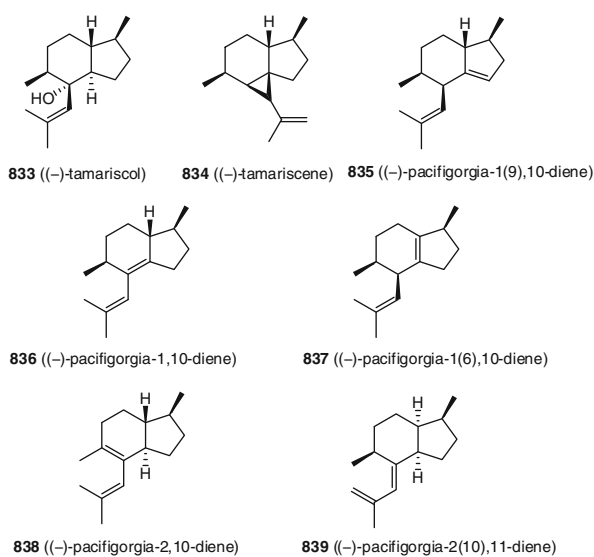


Scheme 4.20 Reaction of (–)-pacifigorgiol and (–)-tamariscol

the liverworts and this higher plant led to the hypothesis that tamariscene (**834**) may be a common precursor for both the pacifigorgianes and valerenanes, as shown in Scheme 4.21 (644).



Scheme 4.21 Formation of valerenane- and pacifigorgiane-type sesquiterpenoids from tamariscene



Pacifigorgiane-type sesquiterpenoids found in the Marchantiophyta

The Ecuadorian *Noteroclada confluens* produces pacifigorgia-6,10-diene (**836**) and pacifigorgia-1(6),10-diene (**837**), together with bicyclogermacrene (**293**), brasila-5(10),6-diene (**342**), and brasila-1,10-diene (**344**) ([492](#)).

4.2.40 Pinguisanes

Liverworts belonging to both the Marchantiopsida and Jungermanniopsida are rich sources of a unique pinguisane sesquiterpenoid skeleton, which has not yet been found in any other organisms. The pinguisanes were isolated for the first time from *Aneura pinguis* (Fig. [4.15](#)). At present, more than 40 pinguisanes have been isolated and their structures elucidated, with some of these totally synthesized ([39](#), [40](#)). Many pinguisanes have been detected in or isolated from several different liverwort species.

The use of the HS-SPME (head space-solid phase microextraction) technique coupled with GC/MS analysis indicated the presence of α -pinguisene (**840**) in *Drepanolejeunea madagascariensis* ([247](#)). The same compound was identified in the ether extract of *Porella perrottetiana* ([424](#)). Pinguisenol (**841**) and naviculol (**845**) have been isolated from the ether extract of the New Zealand *Bazzania novae-zelandiae* together with spathulenol (**136**) ([615](#)). Naviculol (**845**) and its caffeate (**846**) have been found in the same plant ([145](#)).

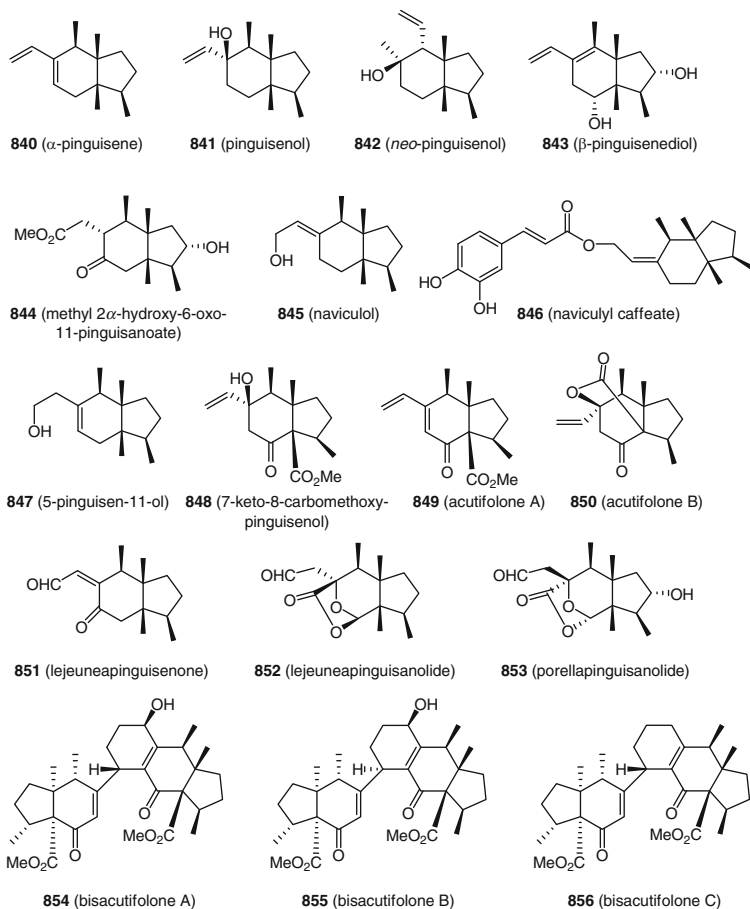
The stereo-controlled total syntheses of racemic α -pinguisene (**840**) and racemic pinguisenol (**841**) were achieved by *Srikrishna* and *Vijaykumar*, employing an orthoester *Claisen* rearrangement and an intramolecular diazo ketone



Fig. 4.15 *Aneura pinguis*. (Permission for the use of this figure has been obtained from Prof. Dr. Rob Gradstein, Paris, France)

cyclopropanation reaction (773). This same group carried out the first total synthesis of (+)-punguisenol (**841**) from (*R*)-carvone as the starting material and established the absolute configuration of the natural product as (1*S*,2*S*,3*R*,6*S*,7*R*). The synthetic compound was the optical antipode of the natural product (774).

A crude extract of New Zealand *Bazzania nova-zelandiae* was found to contain cytotoxic active substances against human tumor cell lines. Bioactivity-guided fractionation gave a pinguisane sesquiterpenoid, naviculyl caffeate (**846**), and naviculol (**845**), for which the absolute configuration had been established (40). The structure of **846** was determined by a combination of 2D-NMR spectroscopy and its semi-synthesis using dicyclohexylcarbodiimide as a dehydrating agent for the esterification of naviculol and caffeic acid (145).



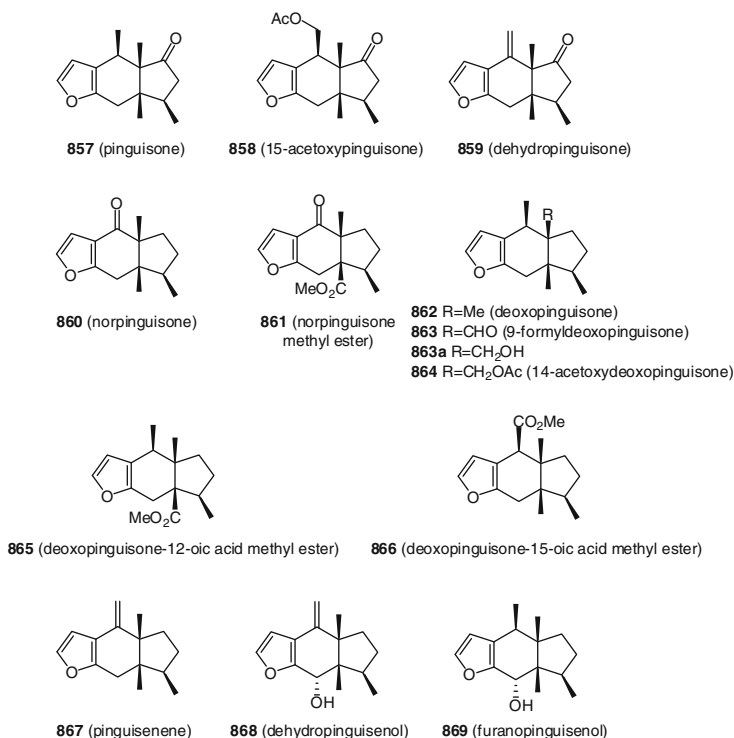
Pinguisane-type sesquiterpenoids found in the Marchantiophyta

The ether extract of *Dicranolejeunea yoshinagana* was purified by CC to give the three new pinguisanes **842**, **863**, and **864**, together with the known deoxopinguisone (**862**), ptychanolide (**890**), and *ent*-(-)-bicyclogermacrene (**293**)

(869). An ether extract of the Finnish *Ptilidium ciliare* contained deoxopinguisone (862) and pinguisanin (874) (596). The structure of the new rearranged pinguisenol (842) was elucidated by COSY and NOE NMR correlations. The presence of an aldehyde and an α,β -disubstituted furan ring in 863 was confirmed by ^1H and ^{13}C NMR and IR spectra and the formation of a primary alcohol 863a from 863 with LiAlH_4 . Further analysis was conducted to show NOE correlations between the tertiary methyl proton at C-9 and the formyl proton, H-3 β at δ 2.22 ppm, and a non-equivalent methylene proton at δ 2.51 ppm, which coupled with a doublet signal at δ 2.80 ppm and exhibited long-range coupling with the H-4 proton. These data showed that the structure of 863 could be assigned as 9-formyldeoxopinguisone, although an alternative structure, 8-formyldeoxopinguisone, could not be excluded. The reduction of 864 having an acetoxy group (IR: 1,750 and 1,250 cm^{-1}) with LiAlH_4 gave a primary alcohol with spectroscopic data identical with those of 863a, indicating that the structure of 864 is 12- or 14-acetoxydeoxopinguisone (869).

Further fractionation of the methanol extract of the English *Porella platyphylla* resulted in the isolation of a new pinguisane, methyl 2 α -hydroxy-6-oxo-11-pinguisanoate (844), together with the known pinguisanin (874), β -pinguisenediol (843), and porellapinguisanolide (853). The structure of 843 was reported to be 2 β ,7 ξ -dihydroxypinguis-4,10-diene. Careful analysis of the NOE correlations of 843 confirmed that β -pinguisenediol had to be revised as 2 α ,7 α -dihydroxypinguis-4,10-diene (843). The structure of 844 was deduced from its ^1H and ^{13}C NMR data, inclusive of NOE correlations. The methyl ester 844 was formed from the corresponding acid by acid-catalyzed esterification with methanol used as extraction solvent (138).

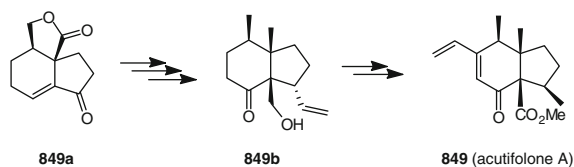
The ether extract of the North American *Porella navicularis* was purified by CC and HPLC to afford four new pinguisanes, 5-pinguisen-11-ol (847), 6 α -methoxypinguis-5(10)-en-11,6-olide (887), 6 α -methoxypinguis-5(10)-en-11,6-olide-15-carboxylic acid (888), and 5 α ,10 α -epoxypinguisane-11,6-olide 15-carboxylic acid methyl ester (889), along with a previously known and major constituent, naviculol (845), in addition to norpinguisone methyl ester (861) (143), a compound isolated from the same liverwort collected in Europe (40). Compound 847 might be an artifact of the double bond isomer, naviculol (845). Its structure was confirmed readily by comparison of the NMR spectra with those of 845. The presence of a γ -lactone in 887 was confirmed by its IR and ^{13}C NMR spectra (1,750 cm^{-1} ; δ 172.4 ppm). Extensive NMR spectroscopic data collection including NOESY led to the full structure of 887, which is an analogue of the keto lactone, 6 α -methoxy-3-oxopinguis-5(10)-en-11,6-olide (880), obtained from an axenic culture of the liverwort *Aneura pinguis* (812). The structure of 888 was proven to be the C-15 carboxylic acid of 887. The methyl ester of 888, compound 877 has been isolated from *Porella canariensis* (582). Compound 889 is the epoxy methyl ester of the demethoxy derivative of 888. Conclusive evidence for the structure of 889 was based on the analysis of its COSY, HMBC, and NOESY NMR experiments and comparison of its overall spectroscopic data with those of 888.



Punguisane-type sesquiterpenoids found in the Marchantiophyta

GC/MS analysis of *Wettsteinia schusterana* showed the presence of deoxopunguisone (**862**). This was the first detection of a pinguisane sesquiterpenoid, which represents one of the most important chemical markers of the families Porellaceae, Lejeuneaceae, Ptilidiaceae, and some Metzgeriales families, in the Adelantaceae (**70**).

The Japanese *Porella acutifolia* has been shown to elaborate two new pinguisanes, acutifolones A (**849**) and B (**850**), and the three new *Diels-Alder* reaction-type dimeric pinguisane sesquiterpenoids, bisacutifolones A (**854**), B (**855**), and C (**856**), which might originate from acutifolone A (**849**). These compounds were obtained together with 7-keto-8-carbomethoxypunguisenol (= 7-oxopunguisenol-12-methyl ester) (**848**), which was isolated from another liverwort (**40**). The key pinguisane keto ester for these new sesquiterpenoids is compound **848**, for which the absolute configuration remained to be clarified. The absolute configuration at C-5 and C-7 of **848** was established by a combination of a positive *Cotton* effect at 287 nm in the CD spectrum of **848** and the application of the modified *Mosher* method with α -methoxy- α -trifluoromethylphenylacetic acid (MTPA) to the 7 α -diol prepared from **848** with sodium borohydride. The structure of compound **849** was clarified by a comparison of 2D-NMR methods including NOESY and interpretation of the spectroscopic data of the dehydrated product prepared from **848** by means of POCl₃. The relative configuration of acutifolone B



Scheme 4.22 Total synthesis of acutifolone A

(**850**) was deduced by 2D-NMR (HMBC) and conclusive evidence was obtained from X-ray crystallographic analysis. The absolute configuration might be the same as that of **848**. The conclusive absolute structure determination of bisacutifolone A (**854**) was carried out by 2D-NMR spectroscopic and X-ray crystallographic analyses as well as by application of an exciton chirality method in the CD spectrum of the *p*-bromobenzoate of **854**, and finally by application of the modified *Mosher* method on **854**. The structure of bisacutifolone B (**855**), the C-10' epimer, was determined by the similar spectrometric procedures as described above including the modified *Mosher* method. 2D-NMR spectroscopic analysis of **856** and the preparation of **856** from bisacutifolone A (**854**) by tosylation, followed by reduction with sodium iodide and zinc, were used to establish the structure of **856** as dehydroxylated bisacutifolin A (**854**) or B (**855**). Both dimeric pinguisanes might originate through the enzymatic *Diels-Alder* reaction of acutifolone A (**849**) itself, since the dimeric products are not obtained by heating **849** in toluene. This is the first report of dimeric pinguisanes from Nature ([315](#), [316](#), [322](#)).

The first total synthesis of acutifolone A (**849**), having the bicyclo[4.3.0]nonane skeleton, was achieved by *Shiina* and *Nishiyama*, using compound **849a** as a starting material and by a *Mukaiyama* aldol reaction, as shown in Scheme [4.22](#) ([742](#)).

Trocholejeunea sandvicensis is a rich source of pinguisanes ([40](#)). Reinvestigation of the ether extract led to the isolation of two new pinguisanes, lejeuneapinguisenone (**851**) and lejeuneapinguisanolide (**852**), together with the known dehydropinguisenol (**868**) and furanopinguisenol (**869**). The structures were determined by a combination of 2D-NMR, molecular mechanics calculations using the MNDO program, and X-ray crystallographic analysis. The lactone aldehyde **852** could be formed through the addition of a molecule of oxygen to the furan ring of **869**, followed by intramolecular condensation ([460](#)).

Rycroft reported the structural elucidation of compounds of certain liverworts within an extract by working with the crude extract itself rather than by devoting laboratory resources to isolating the compounds individually. In this case, the lipophilic constituents of a small amount of the liverworts concerned were extracted with the NMR solvent CDCl_3 . This technique was applied to analysis of the chemical constituents of the liverwort *Adelanthus decipiens*, collected from different geographical origins, and *Cryptothallus mirabilis*, belonging to the Aneuraceae, which is rare and grows near birch trees. From the latter species, the presence of a new pinguisane, 15-acetoxypinguisone (**858**), was confirmed and the structure

was derived by comparison of its spectroscopic data with those of the pinguisone (**857**). The positioning of the acetate at C-15 was confirmed by NOE difference spectroscopy, which demonstrated that C-12 and C-15 are all on the β -face of the molecule (**688**, **692**).

Plagiochila retrospectans produces dehydropinguisone (**859**) (**72**, **579**). Norpinguisone (**860**) was isolated from *Porella canariensis* together with certain drimanes and cyclocolorenone (**126**) (**604**). *Porella elegantula* produces norpinguisone methyl ester (**861**) and deoxopinguisone (**862**) as the minor components (**72**).

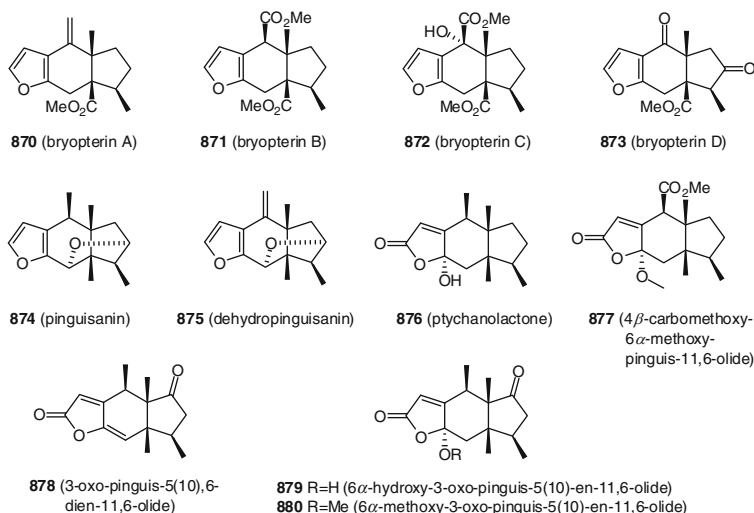
Suspension-cultured cells of *Porella vernicosa* were extracted with ether and the crude extract analyzed by GC/MS. Norpinguisone methyl ester (**861**) was found as the second major metabolite (18.7%), together with deoxopinguisone (**862**, 6.5%), norpinguisone (**860**, 5.3%), deoxopinguisone-15-oic acid methyl ester (**866**, 1.6%), and cinnamolide (**546**, 5.5%). The first major metabolite was the hot-tasting polygodial (**548**, 20.3%). The yields of polygodial in the suspension-cultured cells of *P. vernicosa* and the same field specimen were almost the same, although those of the pinguisane sesquiterpenes were changed dramatically (**637**). Further fractionation of the dichloromethane extract of *Porella canariensis*, collected in Madeira, resulted in the isolation of a new pinguisane, deoxopinguisone-12-oic acid methyl ester (**865**), together with the known α -pinguisene (**840**), pinguisenol (**841**), 7-keto-8-carbomethoxypinguisenol (**848**), norpinguisone (**860**), norpinguisone methyl ester (**861**), deoxopinguisone (**862**), deoxopinguisone-15-oic acid methyl ester (**866**), and ptychanolide (**890**) (**40**). The spectroscopic data of **865** were very similar to those of deoxopinguisone (**862**), except for the presence of a carboxylic carbon and a methyl ester in the ^1H and ^{13}C NMR spectra, and indicated that **865** is deoxopinguisone with a carbomethoxy group at C-8 or C-9. The presence of a carbomethoxy group at C-8 in deoxopinguisone was deduced by careful analysis of the 2D-NMR spectra (**179**).

From the ether extract of the Vietnamese *Porella densifolia*, norpinguisone (**860**) and norpinguisone methyl ester (**861**) were isolated and the structure of **860** was confirmed by X-ray crystallographic analysis (**669**).

Deoxopinguisone (**862**) and ptychanolide (**890**) have been found in the Japanese *Ptychanthus striatus* (**40**). Further fractionation of this species collected in Taiwan led to the identification of the same pinguisanes as mentioned above (**957**).

The ether extract of *Trocholejeunea sandvicensis* was analyzed by GC/MS to identify dehydropinguisenol (**868**) as the major component, together with deoxopinguisone (**862**), pinguisenene (**867**), dehydropinguisanin (**875**), and ptychanolide (**890**). This is the first identification of the two latter pinguisanes from this liverwort (**492**).

The isolation of the pinguisanes, bryopterins A-D (**870–873**) in the Panamanian *Bryopteris filicina* has been reported by Nagashima and coworkers (**40**, **572**). The stereostructures of these compounds were discussed in detail by these same authors (**576**).



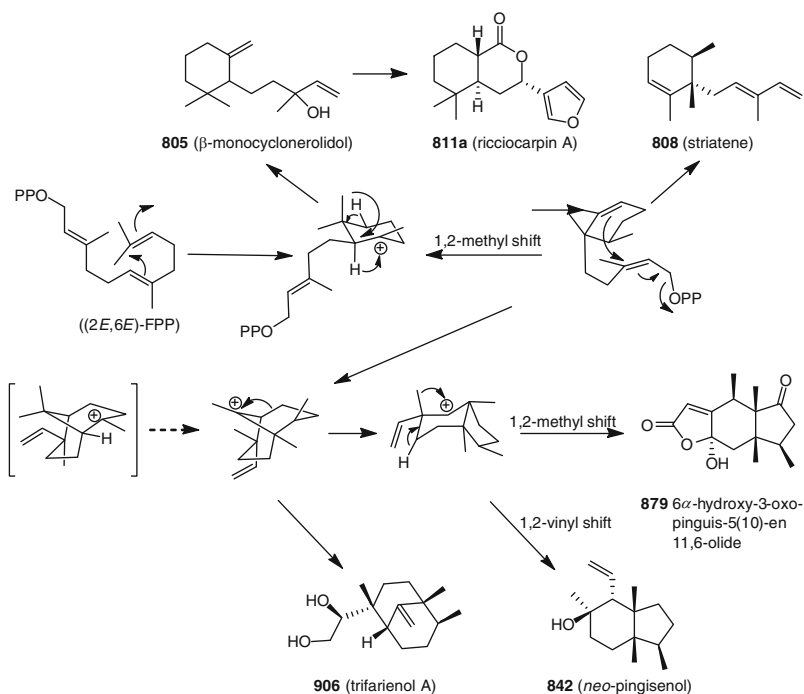
Pinguisane-type sesquiterpenoids found in the Marchantiophyta

The Costa Rican *Bryopteris flicina* was studied chemically and eight sesquiterpenoids were isolated, of which three were the pinguisanes bryopterin C (**872**), ptychanolactone (**876**), and norpinguisone methyl ester (**861**) (**576**), which have also been found in the same Panamanian species (**40**, **572**).

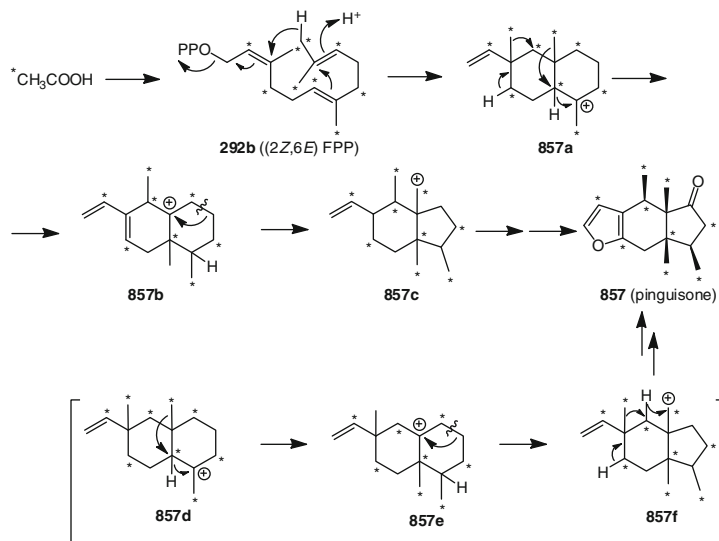
4β-Carbomethoxy-6α-methoxypinguis-6,11-olide (**877**) was isolated from *Porella canariensis* collected in Portugal. The 2D-NMR spectroscopic data were used to confirm the presence of methoxy and carbomethoxy group at C-6 and C-4 of the pinguisane skeleton. It was concluded that **877** is an artifact since the liverwort was extracted with methanol (**582**). Similar pinguisane artifacts have been found in the crude extract of the liverwort *Trocholejeunea sandvicensis* (**40**).

The previously proposed biosynthesis routes of the pinguisanes (**812**) were revised by experiments in which ^2H and ^{13}C -labeled mevalonates were administered to axenic cultures of *Aneura pinguis* (**813**). ^2H - and ^{13}C NMR analysis of 6α-hydroxy-3-oxopinguis-5(10)-ene-11,6-olide (**879**) isolated from axenic cultures of *A. pinguis* in the presence of ^2H - and ^{13}C labeled mevalonates established the biosynthesis of pinguisanes from FPP via a 1,2-hydride shift, two 1,2-methyl group shifts, a cleavage of the main FPP chain, and then recyclization, as shown in Scheme 4.23. The biosynthesis routes for the monocyclofarnesanes **805** and **808**, the rearranged pinguisane **842**, and trifarane (**906**) have been proposed by Tazaki and associates (**813**).

Pinguisone (**857**) was obtained initially from *Aneura pinguis*. Pinguisone was found to accumulate in the cultured gametophytes of *A. pinguis* at a level almost identical to that in a field-collected plant. A biosynthesis study on the formation of pinguisone was carried out by feeding [2- ^{13}C]-acetate to the cultured gametophytes. Pinguisone (**857**) was labeled at an adequate level to establish the labeling positions by ^{13}C NMR analysis. The labeling pattern exhibited a two-methyl group migration and C-C bond cleavage of the main chain in farnesyl diphosphate in the formation of pinguisone (**857**). An alternative route to form the indane cation **857f** via the decalin cation **857e** may also be possible (Scheme 4.24). Further investigation



Scheme 4.23 Biosynthesis pathway for 6 α -hydroxy-3-oxo-pinguis-5(10)-en-11,6-olide (**879**) and possible biosynthesis pathways for monocyclofarnesane-, trifarane, and neopinguisane-type sesquiterpenoids



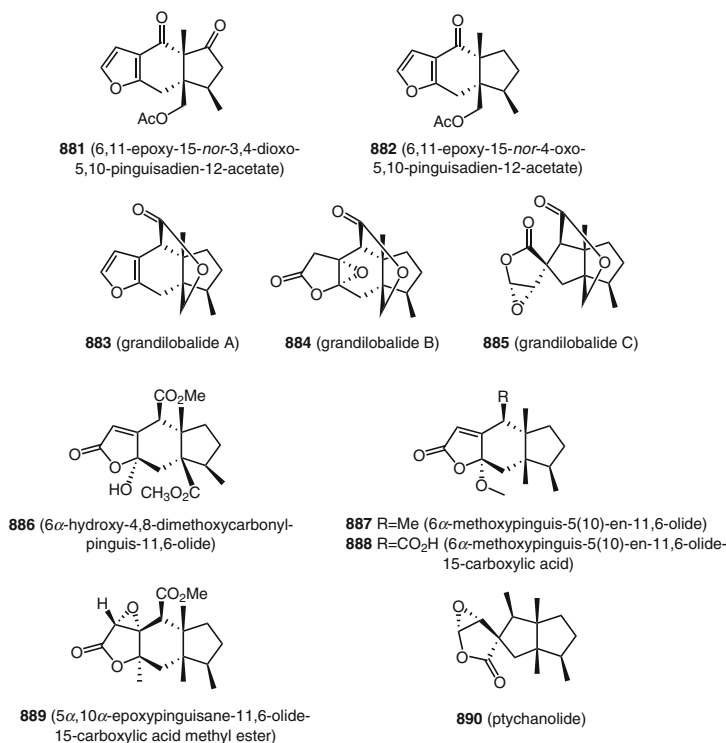
Scheme 4.24 Biosynthesis pathways for pinguisane-type sesquiterpenoids

of the ether extract of the axenic cultures of the same liverwort resulted in the isolation of the three pinguisanes, 6 α -hydroxy-3-oxo-pinguis-5(10)-en-11,6-olide (**879**), 6 α -methoxy-3-oxo-pinguis-5(10)-en-11,6-olide (**880**), and 3-oxo-pinguis-5(10),6-dien-11,6-olide (**878**), together with pinguisone (**857**). The structures of **878–880** were determined by chemical correlations between **857** and **878–880**. Treatment of **857** with *m*-chloroperbenzoic acid gave **879**, followed by methanolysis in hydrochloric acid, and dehydration with potassium carbonate under reflux to give **880** or **878**. These compounds were proved to be natural products since the ether extract contained them as detected by GC, and no other modified derivatives could be detected when compounds **857** and **879** were treated in dichloromethane-methanol for three days (**810**).

The dichloromethane extract of *Porella recurva* collected in Argentina was fractionated to give the two new pinguisanes, **881** and **882**, together with norpinguisone (**860**) and norpinguisone methyl ether (**861**). The structures of **881** and **882** were settled as 6,11-epoxy-15-*nor*-3,4-dioxo-5,10-pinguisadien-12-acetate (= 3-oxo-norpinguisone 12-acetate) and 6,11-epoxy-15-*nor*-4-oxo-5,10-pinguisadien-12-acetate (= norpinguisone 12-acetate), from their HMBC, HMQC, and NOESY NMR spectra (**913**). Compound **882** has been reported previously as the semi-synthetic product from bryopterin C (**872**) isolated from *Bryopteris filicina* (**40**, **576**). A similar compound to **882**, 14-acetoxydeoxopinguisone (**864**) was isolated from the liverwort *Dicranolejeunea yoshinagana* (**869**).

Porella grandiloba provided norpinguisone methyl ester (**861**) together with the monoterpenoids β -elemene (**283**), β -caryophyllene (**426**), and perrottetianal A (**1354**) (**40**). Further fractionation of the ether extract of the gametophytes of *P. grandiloba* gave the four new pinguisanes, grandilobalide A (**883**), 6 α -hydroxy-4,8-dimethoxycarbonyl-pinguis-11,6-olide (**886**), grandilobalide B (**884**), and C (**885**), together with the known bryopterin B (**871**) and norpinguisone methyl ester (**861**). The complete structure of **883** was deduced by the similarity of its NMR spectra to those of bryopterin B (**871**), and the presence of the 15,12-olide unit was confirmed by two new doublet signals at δ 4.42 and 4.72 ppm assignable to H-12, and a NOE experiment. Comparison of the NMR spectra of **886** with those of **871** showed that compound **886** has the same carbomethoxy group at C-4 and C-12 and a 6-hydroxy-11,6- γ -lactone moiety. The complete structure was proven by COSY, COLOC, and NOESY experiments. Oxidation of **871** with *m*-chloroperbenzoic acid gave a lactone for which the spectroscopic data were identical with those of **886**. The ^1H and ^{13}C NMR spectra of **884** were similar to those of **883**, except for the signals of the furan ring. A combination of the IR spectrum, with peaks at 1,810 and 1,740 cm^{-1} assignable to two lactones, and the ^1H and ^{13}C NMR spectra, showed that the furan ring was replaced by a 3,4-epoxy- γ -lactone. The total structure was arrived at by the analysis of its COSY and NOESY spectra. The presence of the same lactone moiety and a spiro lactone in **885** was deduced by a combination of the molecular formula, the IR spectrum (1,790 and 1,730 cm^{-1}), and the similarity of its ^1H and ^{13}C NMR spectra with those

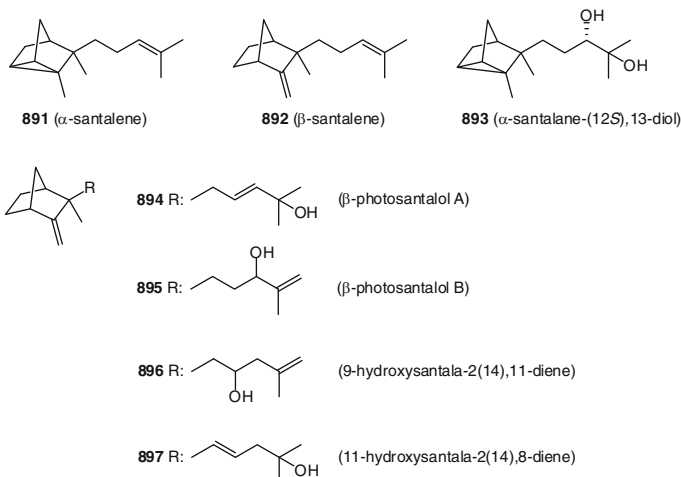
of **883**. Long-range couplings between the methylene protons at C-7, C-6, and C-10, and H-10, C-5, and C-6 observed by means of a COLOC experiment led to structure **885** (814).



Pinguisane-type sesquiterpenoids found in the Marchantiophyta

4.2.41 Santalanes

From the ether extract of *Porella subobtusa* two santalane sesquiterpenoids, α -santalene (**891**) and α -santalane-12,13-diol (**893**), were isolated. Previously, the absolute configuration at C-12 was assigned as (*R*) by the application of an empirical rule to the CD spectrum using Eu(fod)₃ as chelating agent. Re-measuring the CD spectrum using Eu(fod)₃ and applying the Mosher method using the (*R*)- and (*S*)-MTPA esters derived from **893** led to the revision of the configuration at C-12 as (*S*). Thus, the structure of **893** was proven to be α -santalane-(12*S*),13-diol (581). The occurrence of santalanes is very rare in liverworts. The presence of such compounds has been reported only in *Plagiochila yokogurensis* and *Porella caespitans* var. *setigera* (40). Later, α -santalene (**891**) was detected also in *Plagiochila dusenii* (32) and *Radula complanata* (223). Three *Radula* species (223), *Marsupella alpinia* (17), and *Porella navicularis* (143) have been reported to contain β -santalene (**892**).

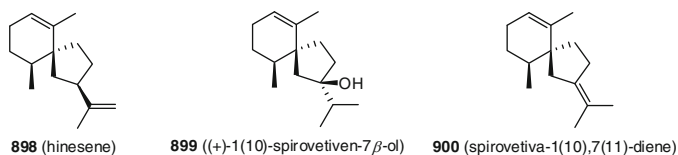


Santalane-type sesquiterpenoids found in the Marchantiophyta

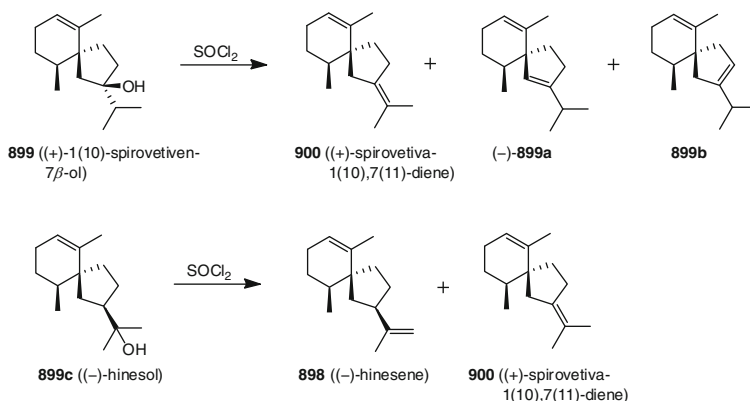
Gackstroemia decipiens belonging to the Lepidolaenaceae displays a characteristic odor when crushed. The distribution of β -santalane derivatives in *G. decipiens* has been reported previously (40). Further fractionation of the ether extract of *G. decipiens* by HPLC afforded the two new β -santalanes, 9-hydroxysantala-2(14),11-diene (**896**) and 11-hydroxysantala-2(14),8-diene (**897**), along with the known β -photosantalol A (**894**) and β -photosantalol B (**895**). Their structures were determined by comparison of NMR data with those of **894** and **895**, and by detailed analysis of their 2D-NMR parameters (252).

4.2.42 Spirovetivanes

Frullania species are rich sources of eudesmane and eremophilane sesquiterpene lactones and/or bibenzyls (40). The ether extract of an unidentified Venezuelan *Frullania* species was purified by CC and preparative TLC to give hinesene (**898**) (843). This was the first isolation of this sesquiterpene hydrocarbon from a liverwort, although it was found earlier in the higher plant, *Rolandra fruticosa* (372). The volatile components of *Frullania tamarisci* subsp. *obscura* produced hinesene (**898**) in 35.5% yield, as estimated from a total ion chromatogram (492).



Spirovetivane-type sesquiterpenoids found in the Marchantiophyta



Scheme 4.25 Correlation of dehydrated products from (+)-1(10)-spirovetiven-7 β -ol and (-)-hinesol

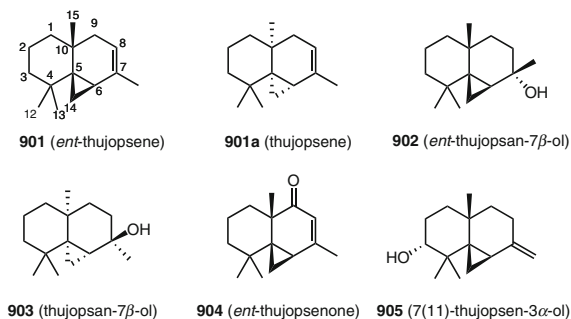
The essential oil obtained by hydrodistillation of the German *Lepidozia reptans* was analyzed by GC/MS (681) to identify (+)-1(10)-spirovetiven-7 β -ol (**899**) and many other sesquiterpene hydrocarbons and their alcohols. Among these, compound **899** was isolated by preparative GC as the major component, together with (-)-1(10)-valencen-1 β -ol (**572**). The structure of **899** was confirmed as (+)-1(10)-spirovetiven-7 β -ol by 2D-NMR methods and by the preparation of the same dehydro product, spirovetiva-1(10),7(11)-diene (**900**) from **899** and (-)-hinesol (**899c**) by dehydration (Scheme 4.25). Compound **900** was also present in the same species. (+)-1(10)-Spirovetiven-7 β -ol (**899**) was also identified in the essential oil of *Lophozia ventricosa* (486).

4.2.43 Thujopsanes

The presence of thujopsanes is very rare in the liverworts. The ether extract of the female sporophytes and thalli of the Japanese *Marchantia polymorpha* was analyzed by GC/MS to identify *ent*-thujopsene (**901**), *ent*-thujopsenone (**904**), and *ent*-thujopsan-7 β -ol (**902**) (492), of which all have been found in the gametophyte of the same liverwort (40). *ent*-Thujopsan-7 β -ol (**902**), isolated from *Marchantia polymorpha*, showed the specific optical rotation $[\alpha]_{\text{D}} 0^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$ (40). On the other hand, the same compound isolated from *Jungermannia infusca* exhibited a negative value ($[\alpha]_{\text{D}} -5.5^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$) (595). To confirm the absolute configuration of **903**, dehydration of this compound was carried out and gave thujopsene (**901a**) for which the optical rotation showed a negative sign ($[\alpha]_{\text{D}} -121.8^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$), which was the same as natural **901a** ($[\alpha]_{\text{D}} -103.9^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$), indicating the structure of **903** to be thujopsan-7 β -ol (595).

Further investigation of the ether extract of *Reboulia hemisphaerica* collected in a different location led to the isolation of thujopsen-7(11)-en-3 α -ol (**905**). The tricyclic skeleton including a cyclopropane ring, an exocyclic methylene, a secondary alcohol, and three tertiary methyl groups was based on the ^1H -, ^{13}C NMR, and

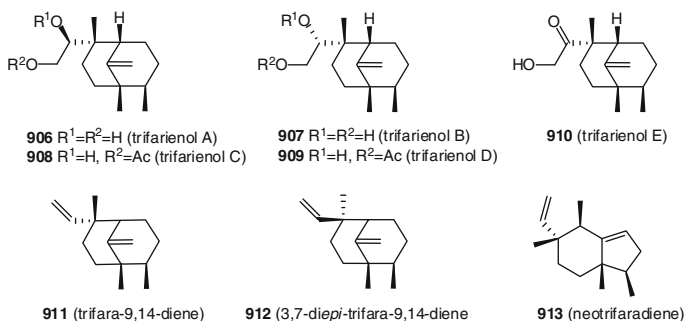
high-resolution MS data obtained. The relative configuration of **905** was settled by the analysis of its 2D-NMR spectra (HMBC and NOSEY) (436, 889).



Thujopsane-type sesquiterpenoids found in the Marchantiophyta

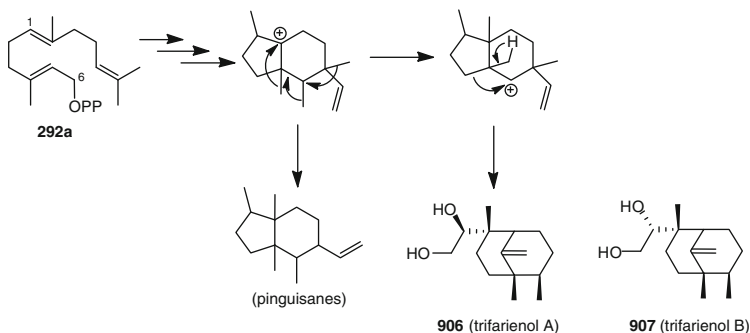
4.2.44 Trifaranes

The trifarane sesquiterpene structural type was discovered initially from a marine sponge (721). Later, the trifarane alcohols **906–910** were isolated from the Malaysian liverwort, *Cheilolejeunea trifaria* (309). Two new trifarane sesquiterpenoids, trifarienols A (**906**) and B (**907**), were isolated from *C. trifaria* also collected in Malaysia, with their absolute configuration established by a combination of the analysis of X-ray crystallographic data and their CD spectra run in the presence of the shift reagent, Eu(fod)₃ as well as the CD spectra of their benzoates (305, 309). The ether extract of *Plagiochila terebrans* was fractionated to give trifarienol B (**907**) (295).

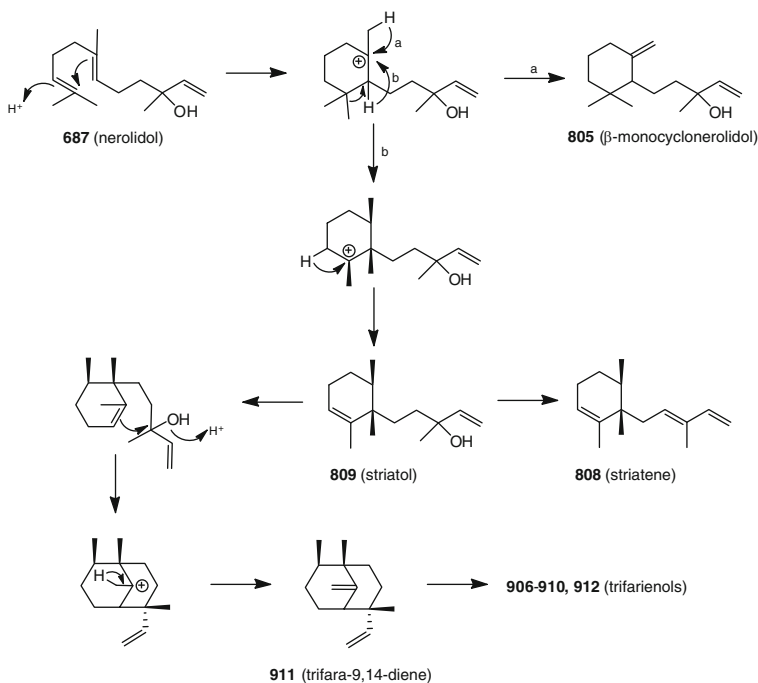


Trifarane-type sesquiterpenoids found in the Marchantiophyta

The determination of the structures of trifarane sesquiterpenoids was reported in detail by Hashimoto and associates (309). Previously, a pinguisane sesquiterpenoid was proposed as being involved in the biogenesis of trifaranes (Scheme 4.26) (837). However, this route is unlikely to be suitable for the biogenesis of trifaranes, and a more plausible biogenesis pathway for the trifaranes **906–910** found in



Scheme 4.26 Possible biogenesis pathway for trifarane-sesquiterpenoids

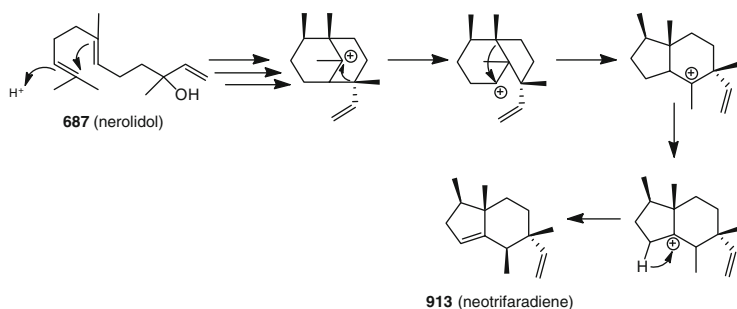


Scheme 4.27 Possible biosynthesis pathways for monocyclofarnesane- and trifarane-type sesquiterpenoids

Cheilolejeunea trifaria is shown in Scheme 4.27. β -Monocyclonerolidol (**805**), which also occurs in *Cheilolejeunea excisable* (**264**), might be formed from nerolidol (**687**) (route a). Alternatively, one of the methyl groups at C-4 could migrate to C-5, to give a striatane sesquiterpenoid (**809**) from which striatene (**808**) and the trifarinenols **906–910** might be biosynthesized (route b). This study represented the first isolation of trifaranes with a (3*S*)-configuration from a natural source. It is noteworthy that a marine sponge and a liverwort elaborate the same trifaranes and that the former organism produces a trifarane with (*R*)-configuration at C-3 (**721**).

Due to their unique structural features, with a bicyclo[3.3.1]nonane system containing an exomethylene unit in the trifarienols, their total syntheses were carried out by three groups. *Huang* and *Forsyth* accomplished the total synthesis of trifarienols A (**906**) and B (**907**) from 2-methyl-2-cyclohexanone *via* construction of the bicyclo[3.3.1]nonane framework by an efficient, anti-selective α' -intramolecular carbomercuration process, in sixteen steps and in 9% and 3% overall yields (**353**). An enantioselective total synthesis of trifarienols A (**906**) and B (**907**) was achieved by *Tori* and associates using the optically active (2*RS*,3*R*)-2,3-dimethylcyclohexanone, which was prepared from phenylethylamine in ten steps, to obtain both natural products in 1.8% and 1.4% yields (**852**). Diastereoselective total syntheses of compounds **906** and **907** were developed by *Takahashi* and co-workers (**798**) *via* an intramolecular *Hosomi-Sakurai* reaction of an allylsilane derivative as the key reaction from 2-methyl-2-cyclohexanone, in 16 steps and in 9% and 3% overall yields.

Trocholejeunea sandvicensis produces not only pinguicane but also trifarane sesquiterpenoids. The ether extract was further fractionated to give (–)-trifara-9,14-diene (**911**), (–)-3,7-di-*epi*-trifara-9,14-diene (**912**), (+)-neotrifaradiene (**913**), and (+)-sandvicene (**919**), together with the other sesquiterpene hydrocarbons of the acorane, aristolane, barbatane, cedrene, eremophilane, eudesmane, pinguicane, thujopsane, and ylangane types, which were detected by GC/MS. The relative stereostructures of the new compounds were elucidated by a combination of their HMBC and NOESY spectroscopic data (**539**). The hydrocarbons **911** and **912** were found to be precursors of the trifarienols **906–910**. Neotrifaradiene (**913**) may be biosynthesized from monocyclofarnesol-type sesquiterpenes, as shown in Scheme 4.28.



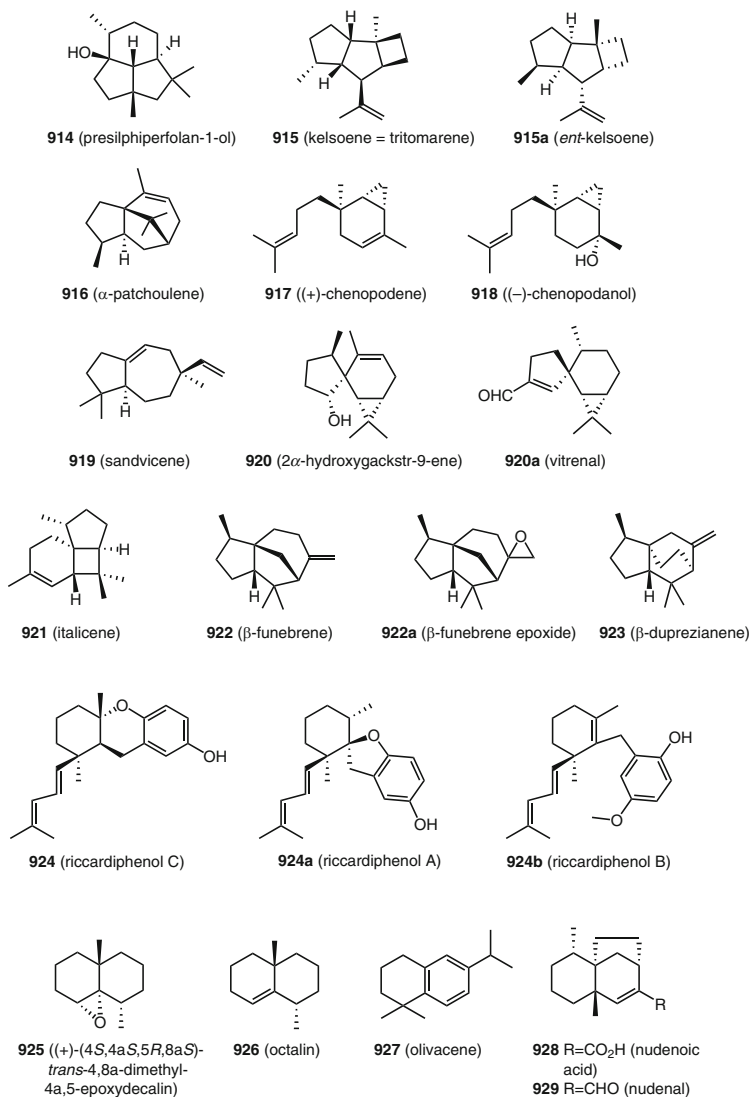
Scheme 4.28 Possible biosynthesis pathway for neotrifarane-type sesquiterpenoid

4.2.45 Miscellaneous

Presilphiperfolan-1-ol (**914**), which has been isolated from *Eriophyllum staechadifolium* (**120**) and known as a rearrangement product from isocaryophyllene (**429b**), was isolated from the essential oil of *Conocephalum conicum* (**543**).

A new and unusual sesquiterpene with a 1,5-dimethyl-7-(1'-methylethenyl) tricyclo[6.2.0.0.^{2,6}]decane skeleton, kelsoene (= tritomarene) (**915**), was isolated

from the tropical marine sponge *Cymbastela hooperi*, with prespatane (**340**), *epi*- γ -gurjunene, and T-candinthiol type sesquiterpenoids, and its structure elucidated by a combination of 2D-NMR spectroscopic methods (HMBC, INADEQUATE, and NOESY correlations) (**431**). The same compound was isolated from the liverworts *Ptychanthus striatus* (**320**, **396**), *Calypogeia muelleriana* (**933**), and *Tritomaria quinquedentata* (**928**). The cultured cells of *Ptychanthus striatus* were extracted with solvent and fractionated by CC to give kelsoene (**915**) along with prespatane (**340**) and striatol (**809**) (**565**). The reinvestigation of the essential oils of *Saccogyna viticulosa* by GC and GC/MS resulted in the identification of kelsoene (**915**) (**276**).



Miscellaneous sesquiterpenoids found in the Marchantiophyta

A biosynthesis study on (+)-kelsoene (**915**) was performed by *Nabeta* and associates in the cultured cells of *Ptychantus striatus* using ^2H and ^{13}C -labeled mevalonate. This experiment showed that the labeling pattern of the kelsoene demonstrated randomization of the ^1H - and ^{13}C - labels between the isopropenylmethyl and methyl groups, with the loss of one H-1 proton from farnesyl diphosphate, suggesting that kelsoene (**915**) is biosynthesized from a germacre-dienyl cation with (7*R*)-configuration via the (–)-alloaromadendranyl cation (**567**). The first total synthesis of kelsoene (**915**) was accomplished by employing commercially available 1,5-cyclooctadiene as the starting material (**536**, **537**). *Piers* and *Orellana* achieved the total synthesis of (±)-kelsoene (**915**) in 15 steps from commercially available cyclopent-2-en-1-one (**659**). The stereoselective total synthesis of (±)-kelsoene (**915**) was also conducted in 14 steps by *Bach* and *Spiegel* starting from (±)-*trans*-2-allyl-1-(2-propenyl)-cyclopentane (**88**).

Nabeta and associates have reported the absolute configuration of kelsoene as *ent*-(–)-kelsoene (**915**) (**566**). Their total synthesis showed that the absolute configuration assigned earlier to the natural product needed to be reversed and should be correctly represented as (+)-kelsoene (**915**). *Mehta* and *Srinivas* achieved the enantioselective total synthesis of (+)-kelsoene (**915**) and (–)-kelsoene (**915a**) using (+)- and (–)-bicyclo[3.3.0]octane-2,6-diones as starting materials, and they concluded that this configuration was incorrect and the absolute configuration of the natural kelsoene is as depicted in **915**, on the basis of the total synthesis of the natural (+)-kelsoene (**538**). The total synthesis of naturally occurring (+)-kelsoene (**915**) was also carried out by *Fietz-Razavian* and coworkers and its absolute configuration established (**219**).

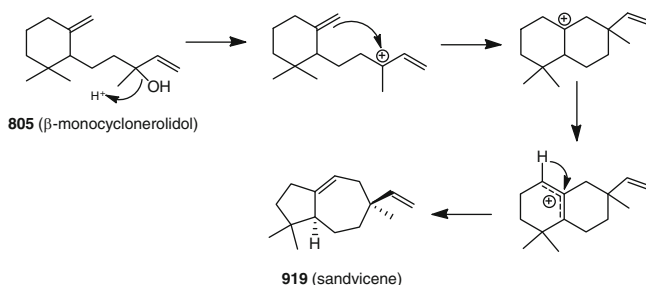
Previously, α -patchoulene (**916**) has been detected in three liverwort genera, namely, *Mastigophora*, *Plagiochila*, and *Scapania* (**40**). *Ludwiczuk* and colleagues reinvestigated the volatile components of *Mastigophora dicladus* by GC/MS to confirm the presence of **916** (**494**). The same hydrocarbon was also detected in *Porella navicularis* (**143**).

An ether extract of the Venezuelan *Marchantia chenopoda* was purified by CC to yield two chenopodanes, chenopodene (**917**) and chenopodanol (**918**). The structure proposed for **918** was based on extensive NMR analysis including HMQC, HMBC, and NOESY correlations (**849**).

Tori and coworkers achieved the total synthesis of chenopodene (**917**) and chenopodanol (**918**) isolated from *Marchantia chenopoda* using (+)-2-methyl-2-(1-carbomethoxy)-ethylcyclohexanone as the starting material. The fact that the signs of the optical rotation of the compounds produced were opposite to those isolated from *M. chenopoda* indicated that these synthetic compounds are enantiomers of the natural products (**849**).

Trocholejeunea sandvicensis produces (+)-sandvicene (**919**). The relative stereostructure of this new compound was elucidated by a combination of HMBC and NOESY spectroscopic data analysis (**539**). Sandvicene (**919**) may be biosynthesized from monocyclofarnesol-type sesquiterpenes, as shown in Scheme 4.29.

Gackstroemia species were found to produce a new skeletal sesquiterpene alcohol (**920**), structurally similar to vitrenal (**920a**) (**40**). The structure was deduced using ^1H - ^1H , ^1H - ^{13}C NMR, and NOESY spectroscopic data. The name “gackstrane” is proposed for this skeleton and thus the structure of **920** is 2α -hydroxygackstr-9-ene (**615**).



Scheme 4.29 Possible biosynthesis pathway for a sandvicane-type sesquiterpenoid

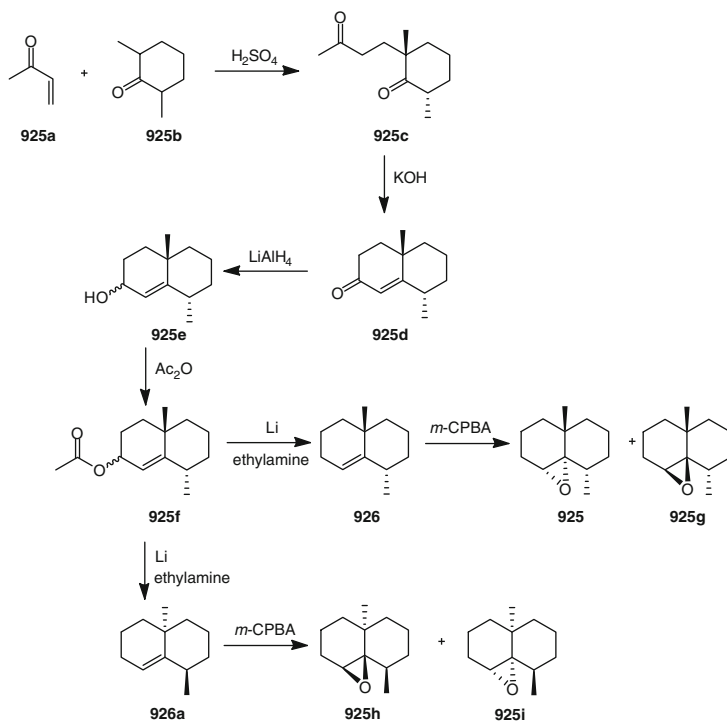
The essential oil of *Plagiochila asplenioides* was also analyzed by GC/MS to identify italicene (**921**) (14, 463) and β -funebrene (**922**) (12, 14).

β -Duprezianene (**923**) has been detected in the hydrocarbon fraction of the liverwort *Trocholejeunea sandvicensis* (539). Compound **923**, possessing the duprezianane skeleton, has been found previously in the essential oil of the wood of *Juniperus thurifera* (102).

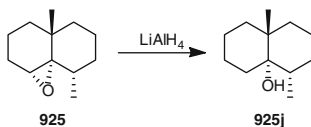
The Japanese *Riccardia crassa* produces riccardiphenols A (**924a**) and B (**924b**), which contain a sesquiterpene portion attached to a quinol ring (40). A New Zealand collection of *R. crassa* elaborated a similar compound named riccardiphenol C (**924**) as a major component, for which the structure was elucidated by COSY and NOE NMR interaction experiments. Conformational searching of **924** was carried out using the MacroModel software and the MM2 force field methods. The observed coupling constants and NOE interaction were consistent with the conformation proposed by these methods. Riccardiphenols A and B were not found in the New Zealand collection (651).

Tori and associates achieved the total synthesis of riccardiphenols A (**924a**) and B (**924b**) in their optical pure forms from the chiral *Michael* addition product, methyl (1'*R*)-3-(1'-methyl-2'-oxocyclohexyl)prop-2-enoate produced from 2-methylcyclohexanone and (*S*)-phenyl-ethylamine, followed by a combination of a *Grignard* reaction and an acid-catalyzed cyclization reaction of the corresponding triol. The absolute configurations of both compounds have been established, as formulated by **924a** and **924b** (847).

The essential oil from the German *Lophocolea bidentata* was analyzed by GC/MS to detect the new epoxytrinoreudesmane sesquiterpene **925** as a major component, together with β -barbatene (**235**), α -selinene (**575**), and diplophyllolide (**678**). Compound **925** was isolated by preparative GC and its structure was established as (+)-(4*S*,4*aS*,5*R*,8*aS*)-*trans*-4,8*a*-dimethyl-4*a*,5-epoxydecalin by ^1H - and ^{13}C NMR analysis. Its total synthesis also supported the structure proposed, and, when started with a *Michael* addition of methyl vinyl ketone (**925a**) to 2,6-dimethylcyclohexanone (**925b**), led almost exclusively to (*E*)-2,6-dimethyl-2-(3'-oxobutyl)cyclohexanone (**925c**), followed by base-catalyzed cyclization with KOH, reduction with LiAlH_4 , and then acetylation, to afford the monoacetate **925f**, which was treated with Li in ethylamine to afford racemic 4,8*a*-dimethyl-1,2,3,4,6,7,8,8*a*-octalin (**926**, **926a**). Each resulting octalin was epoxidized by



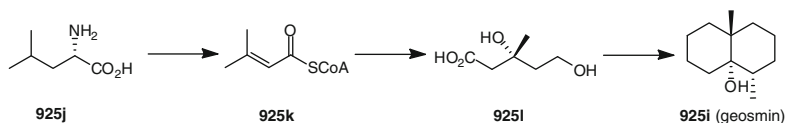
Scheme 4.30 Epoxidation of octalin enantiomers by *m*-chloroperbenzoic acid



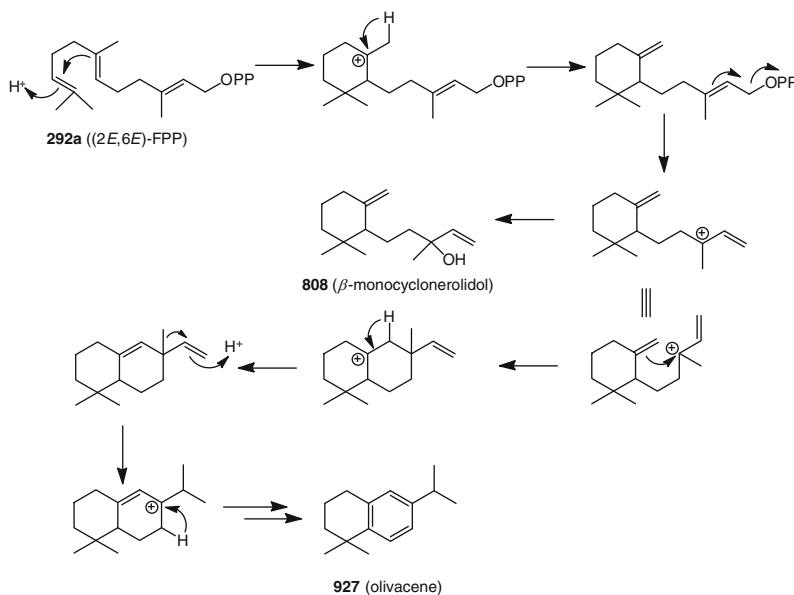
Scheme 4.31 Confirmation of the absolute configuration of natural (4*S*,4*aS*,8*aR*)-geosmin

m-CPBA to afford four epoxides, of which one (**925**) was identical to the natural product physically and spectroscopically (Scheme 4.30). The configuration of **925** was confirmed by the formation of (–)-(4*S*,4*aS*,8*aR*)-geosmin (**925j**) from **925** by LiAlH_4 reduction (Scheme 4.31). Compound **925** was detected in *L. heterophylla* (679). In addition, compound **926**, which might be the biosynthetic precursor of **925**, was identified in *L. bidentata* and *L. heterophylla*.

Geosmin (**925j**) has been found in some liverworts and mosses as well as microorganisms, such as many *Streptomyces* species, cyanobacteria, mycobacteria, and fungi. This degraded sesquiterpene alcohol affords an unpleasant taste to potable water. A single protein consisting of 726 amino acids found in *Streptomyces coelicolor* A3(2) catalyzes the magnesium ion-dependent cyclization of farnesyl diphosphate to a mixture of germacradienol (**698**), germacrene D (**692**), and



Scheme 4.32 Biosynthesis pathway of geosmin



Scheme 4.33 Possible biogenesis pathways for an olivacene-type sesquiterpenoid

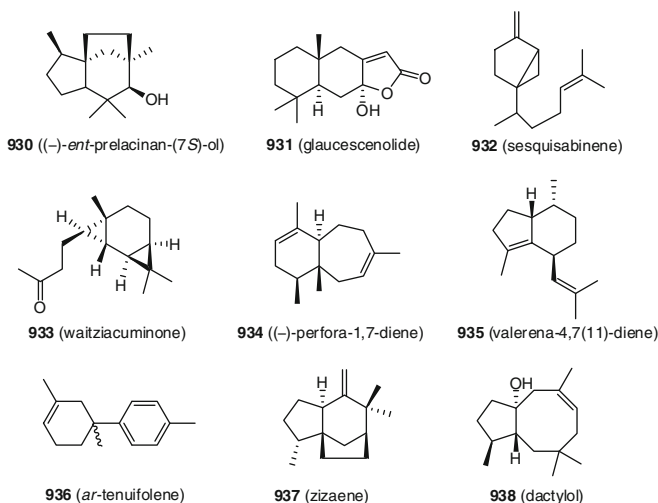
geosmin (**925j**). There is evidence that the conversion of germacradienol to geosmin by *S. coelicor* germacradienol/geosmin synthase results in the release of a three-carbon side chain as acetone and involves a 1,2-hydride shift of the bridgehead hydrogen exclusively into ring B of geosmin (**925j**) (377).

Biosynthesis of geosmin (**925j**) in the liverwort *Fossombronia pusilla* was proposed by Warmers and König and Thiel and Adam (831, 932). An alternative biosynthesis of geosmin (**925j**) emitted by the myxobacteria *Myxococcus xanthus* and *Stigmatella aurantiaca* was also proposed by feeding experiments with [$^2\text{H}_{10}$] leucine and [4,4,4,5,5,5- $^2\text{H}_6$]dimethylacrylate, as shown in Scheme 4.32 (192).

The ether extract of *Archilejeunea olivacea* was found to contain a rare trinorsesquiterpene hydrocarbon named olivacene (**927**), for which the structure was formulated based on long-range ^1H - ^{13}C COSY, HMQC, and HMBC NMR correlations (879) and co-identity of its spectroscopic data with those of the synthetic product (203). Olivacene might be formed from the monocyclofarnesane-type sesquiterpene, β -monocyclonerolidol (**808**) (see Sect. 4.2.36.), which was also isolated from the same liverwort, as shown in Scheme 4.33.

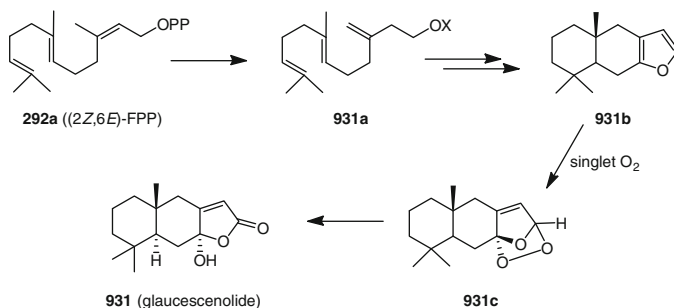
The combined *n*-hexane and ethyl acetate extracts of the Taiwanese *Mylia nuda* was fractionated on silica gel to isolate nudenonic acid (**928**), a novel tricyclic sesquiterpene acid, and nudenal (**929**), which is unstable, gradually oxidizing to nudenoic acid. The structure of **928** was suggested by 2D-NMR experiments (^{13}C DEPT and HMBC). Conclusive evidence for this structure was obtained by X-ray crystallographic analysis of **928**. *Mylia taylorii* also produced nudenal (**929**). In contrast, *Mylia verrucosa* elaborates neither nudenoic acid nor nudenal (**476**). These new compounds may be biosynthesized from a bicyclic spirovetivane-type sesquiterpenoid, isolated from the liverworts *Scapania robusta*, *S. maxima* (**40**), and *Frullania* species (**843**). Nudenoic acid (**928**), purified from the Taiwanese liverwort *Mylia nuda*, was synthesized by *Ho* and *Su* (**344**) in ten steps from the trimethyl silyl ether of 2,6-dimethylcyclohexanone (**476**).

Jungermannia infusca is known to elaborate the prelacinan sesquiterpene alcohol, *ent*-prelacinan-(7*S*)-ol (**930**), for which the absolute stereostructure was established using a combination of 2D-NMR spectroscopic methods including a NOESY experiment, and comparison with the analogous data of prelacinan-7-ol (**235**) as well as the negative *Cotton* effect (299 nm) of the ketone prepared from **930** by PCC (pyridinium chlorochromate) (**600**).



Miscellaneous sesquiterpenoids found in the Marchantiophyta

Bioactivity-directed isolation of the dichloromethane extract of *Schistochila glaucescens* led to the isolation of a new sesquiterpene lactone named glaucescenolide (**931**), which has a new carbon skeleton not previously reported from liverworts or any other plants. The structure was determined by 2D-NMR procedures. This lactone might be formed from farnesyl diphosphate (**292a**) to



Scheme 4.34 Biogenesis pathway for glaucescane-type sesquiterpenoids

afford the furanosesquiterpene **931b**, which can react with singlet oxygen to give the peroxide **931c**, and rearrange in the presence of water to afford **931**, as shown in Scheme 4.34 (712).

The volatile components of *Chandonanthus hirtellus* and *Plagiochila sciophila* collected in Borneo were reinvestigated to identify sesquisabinene (**932**) (490, 492).

The known sesquiterpene ketone, waitziacuminone (**933**), was isolated from *Jamesoniella colorata* (340). Compound **933** has been found in the higher plant, *Waitzia acuminata* (372).

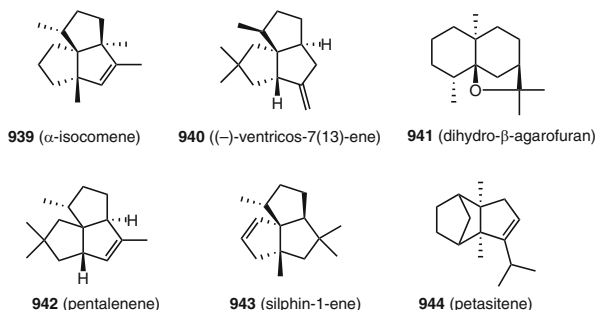
(-)-Perfora-1,7-diene (**934**) was isolated from the hydrodistilled essential oil of *Scapania undulata* (16). Andersen and associates discussed the presence of the unidentified sesquiterpene hydrocarbon undulatene for which the structure remained to be clarified. Its spectroscopic data were identical to those of perfora-1,7-diene (28). Perforane sesquiterpenoids have been isolated from the red algae, *Laurencia perforata* (259) and *L. snyderiae* var. *guadalupensis* (349), and their structures established by total synthesis (260).

Valerena-4,7(11)-diene (**935**) has been detected in the essential oil of *Radula perrottetii* using GC/MS (826). It is noteworthy that the higher plant, *Valeriana officinalis* produces (-)-valerena-4,7(11)-diene (**935**) together with pacifigorgianes, as for example, (+)-tamariscene (**834**), the enantiomer isolated from *Frullania* species. The co-occurrence of both pacifigorgianes and valerenanes in *V. officinalis* and both enantiomers of tamariscene (**834**) in the liverworts and the higher plants led to the hypothesis that tamariscene (**834**) may be a common precursor for both pacifigorgianes and valerenanes, as shown in Scheme 4.21 (644).

The Japanese *Radula perrottetii* produced *ar-tenuifolene* (**936**), which was isolated from the higher plant, *Osyris tenuifolia*, as the (-)-enantiomer (448). This compound was found to occur as a racemate in the essential oil of this plant (826). Liverworts biosynthesize racemic mixtures of sesquiterpene hydrocarbons only occasionally.

The ether extract of *Pellia epiphylla* (492) and the essential oil of *Radula aquilegina* (223) contain zizaene (937).

The essential oil of *Conocephalum conicum* contained *ent*-dactylol (938), which showed a negative optical rotation (543). The (+)-isomer of 938 has been found in the Caribbean sea hare *Aplysia dactylomela* (720). *Makinoa crispata* elaborates dactylol (938) together with bicyclogermacrene (293). It produces also a large amount of perrottetianal A (1354). Compound 938 and α -isomene (939) have also been identified in *Noterochlada confluens* (492).



Miscellaneous sesquiterpenoids found in the Marchantiophyta

Previously, many sesquiterpenoids have been identified in *Lophozia ventricosa* (40). Further investigation of the essential oil of the same liverwort resulted in the isolation of a new pentalenane, (–)-ventricos-7-(13)-ene (940), and a new eudesmane, (+)-6,7-epoxyeudsm-3-ene (636), as mentioned earlier. The pentalenane structure for 940 was deduced using the COSY and HMBC NMR pulse sequences. The relative configuration was also based on NOESY analysis (486).

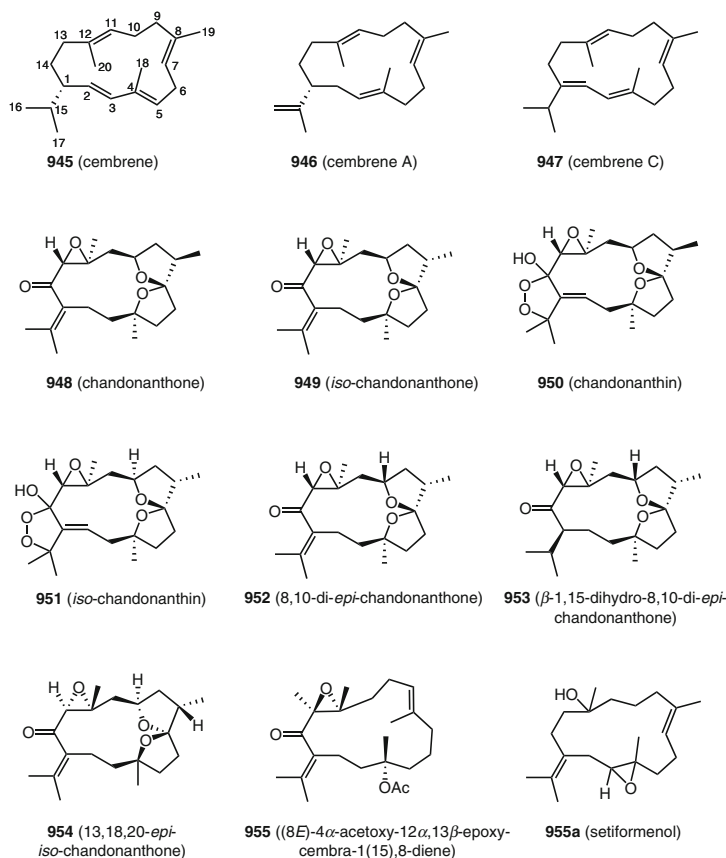
The Ecuadorian *Symphyogyna brasiliensis* was reinvestigated chemically to identify the presence of dihydro- β -agarofuran (941) and δ -selinene (578) as the major components (40, 490).

Pentalenene (942) and silphin-1-ene (943) have been detected in *Frullania serrata* as minor components (490), and the former compound and petasitene (944) occur in a number of Portuguese *Radula* species (223).

4.3 Diterpenoids

4.3.1 Cembranes

Chandonanthus species belonging to the Scapaniaceae are interesting chemically since they produce cembranes (40). Three cembrane diterpenoids, chandonanthone (948), *iso*-chandonanthone (= 8-*epi*-chandonanthone) (949), and setiformenol (955a) were isolated from *C. hirtellus* (40, 838).



Cembrene-type diterpenoids found in the Marchantiophyta

Further fractionation of the ethyl acetate extract of *Chandonanthus hirtellus* led to the isolation of the new *iso*-chandonanthone (**949**) and the known chandonanthone (**948**), for which the stereostructures were elucidated by a combination of 2D-NMR data interpretation and X-ray crystallographic analysis. Compounds **948** and **949** are unstable in chloroform solution and the two corresponding peroxy derivatives chandonanthin (**950**) and *iso*-chandonanthin (**951**) were obtained (**748**). Compound **950** was also detected in the ether extract of the Tahitian *Chandonanthus hirtellus* (**423**).

The volatile components of the *Chandonanthus hirtellus* obtained in French Polynesia and Borneo were analyzed by GC/MS to confirm the presence of chandonanthone (**948**) as a major component in each case. Cembrene (**945**) and cembrene A (**946**) were detected as minor components in the former specimen (**423**, **494**) and *iso*-chandonanthone (**949**) was shown to be present in the latter collection (**490**).

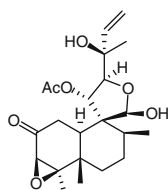
Further investigation of the ether extract of the West Malaysian *C. hirtellus* led to the isolation of two new cembranes, 8,10-di-*epi*-chandonanthone (**952**) and β -1,15-dihydro-8,10-di-*epi*-chandonanthone (**953**), for which their stereostructures were established by X-ray crystallographic analysis (**927**).

Chandonanthus hirtellus, collected in Tahiti, was extracted with ether and methanol. The methanol extract was purified by CC to give two new cembranes, 13,18,20-tri-*epi-iso*-chandonanthone (**954**) and chandonanthone acetate (**955**), together with chandonanthin (**950**) and *iso*-chandonanthone (**949**). The structure of **954** was established by comparison of its spectroscopic data with those of **950** and by X-ray crystallographic analysis. The NMR spectra of **955** were very similar to those of **954** and **950**, indicating that **955** possesses the same chandonanthone skeleton. The complete structure of **955** was assigned by the careful analysis of its 2D-NMR spectra (421–423).

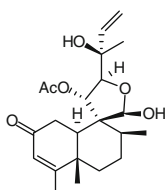
It is noteworthy that an unidentified Tahitian *Jungermannia* liverwort produces cembrane A (**946**) and cembrane C (**947**) although *Jungermannia* species belonging to the Jungermanniaceae are different morphologically from *Chandonanthus* of the Scapaniaceae (494).

4.3.2 Clerodanes

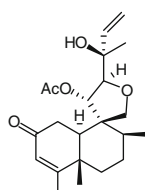
Liverworts are rich sources of clerodane diterpenoids. Four *ent*-spiroclerodanes named heteroscyphones A–D (**956**–**959**) and a new clerodane, heteroscyphol (**960**), were isolated from an ether extract of *Heteroscyphus planus*. Of these, heteroscyphone A (**956**) was found to be the major component (310). The structure of **956** was proposed based on a combination of its COSY, HMBC, and NOESY spectroscopic data and by X-ray crystallographic analysis. The absolute configuration of **956** was established from the negative CD *Cotton* effect (298 nm). Compound **957** was readily prepared from **956**. The spectroscopic data of an α,β -unsaturated ketone obtained from **956** by a *Miyasita* reaction, were identical to those of the natural heteroscyphone B (**957**). The negative *Cotton* effect of **957** at 329 nm was used to establish the absolute stereochemistry of **957**. That compound **958** is the deoxy derivative of **957** was confirmed by the similarity of their ^1H - and ^{13}C NMR spectra as well as by NOESY spectroscopic analysis. The negative *Cotton* effect at 329 nm confirmed its absolute configuration. Similarly, the structure of heteroscyphone D (**959**) was established by the comparison of its spectroscopic data with those of **957** and from the negative *Cotton* effect at 333 nm. This was the first report of the isolation of highly oxygenated clerodanes possessing a spiro structure from the Marchantiophyta. The stereostructure of compound **960** was assigned as *ent*-cleroda-3,12(*E*),14-trien-11-ol using both a chemical reaction, in which **960** gave an α,β -unsaturated ketone, and by 2D-NMR spectroscopic (COSY, HMBC, and NOESY) data analysis. The absolute configuration of **960** was suggested by its co-occurrence with other spiroclerodanes (310).



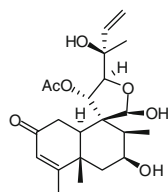
956 (heteroscyphone A)



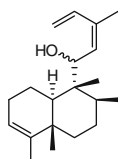
957 (heteroscyphone B)



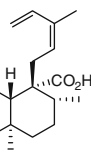
958 (heteroscyphone C)



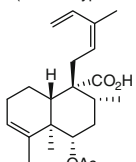
959 (heteroscyphone D)



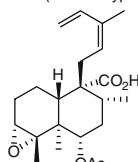
960 (heteroscyphol)



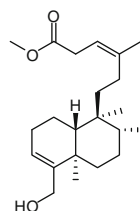
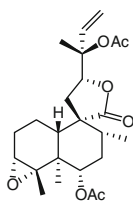
961 (heteroscyphic acid A)



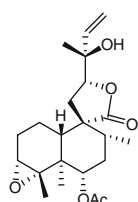
962 (heteroscyphic acid B)



963 (heteroscyphic acid C)

964 (18-hydroxy-5,10-*trans*-cleroda-3,13*E*)-dien-15-oic acid methyl ester)

965 (heteroscypholide A)



966 (heteroscypholide B)

Clerodane-type diterpenoids found in the Marchantiophyta

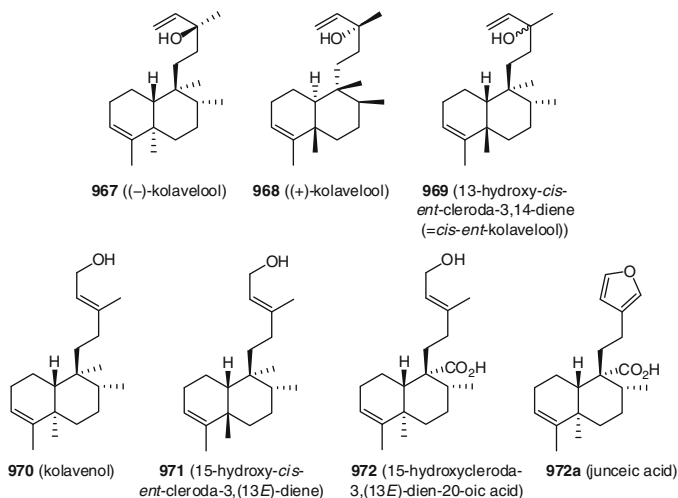
Three clerodane 20-carboxylic acids, heteroscyphic acids A (**961**), B (**962**), and C (**963**), which are possible intermediates for clerodane diterpenes with a spiro- γ -lactone group at the C-9 position, were isolated from the calli and cells from suspension cultures of *Heteroscyphus planus*. The same carboxylic acids are present in the gametophytes of *H. planus* and their amounts in the acidic fractions from gametophytes were 4–13 times higher than those in suspension cells. However, these clerodane acids have not been found in field-collected *H. planus*. The structure of **961** was established using a combination of its IR, FI-HRMS, ^1H , ^{13}C , COSY, DEPT, HMBC, and NOESY NMR experiments. The *cis*-orientations of the carboxyl group and the methyl group at C-5 were also assigned by difference NOE of the methylated product of **961** (**561**).

A review of the deoxyxylulose phosphate pathway of terpenoid biosynthesis in plants including the liverworts as well as microorganisms was published by *Eisenreich* and associates (201). Heteroscyphic acid A (**961**) in *Heteroscyphus* is biosynthesized through the deoxyxylulose pathway (830).

Compound **962** is the C-6 acetoxy derivative of **961**, with its structure characterized by means of the same methods as mentioned above. The acetoxy group at C-6 is in a sterically hindered environment, thus **962** resists weak basic hydrolysis. Refluxing of **962** in 20% KOH in methanol gave the C-6 hydroxy product. The presence of an epoxide ring at C-3/C-4 and its orientation in heteroscyphic acid C (**963**) was confirmed by the multiplicity of the H-3 resonance in its ^1H NMR spectrum (broad s, $W_{1/2} = 3.8$ Hz) and a NOE experiment on the methyl ester of **963** (561).

The methanol extract of the cultured cells of *Heteroscyphus planus* was purified by HPLC to give three new clerodanes, cleroda-15-oic acid methyl ester, and heteroscypholides A and B, with the new structures deduced as 18-hydroxy-5,10-*trans*-cleroda-3,(13*E*)-dien-15-oic acid (**964**), 3,4-epoxy-6,13-diacetoxy-5,10-*trans*-cleroda-14-en-20,12-olide (**965**), and its 13-deacetyl derivative, 3,4-epoxy-6-acetoxy-13-hydroxy-5,10-*trans*-5,10-*trans*-clerod-14-en-20,12-olide (**966**), by extensive 2D-NMR spectroscopic analysis (DEPT, HMBC, NOESY) (563). The structures of **965** and **966** were established conclusively by the X-ray crystallographic analysis of **965** and the formation of **966** from **965** by selective hydrolysis using cesium carbonate. Since the absolute configuration of the clerodane lactol, heteroscyphone B (**957**), isolated from field-collected *H. planus*, was established from its CD spectrum (310), the structurally related compounds **964–966** may each have the same absolute configuration (811).

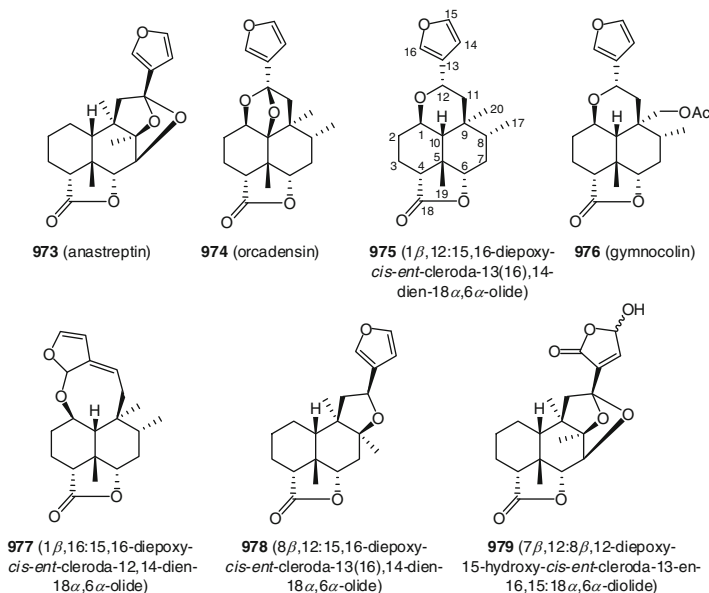
The known (–)-cleroda-3,14-dien-13-ol (= (–)-kolavelool) (**967**) was isolated from the Taiwanese *Pallavicinia subciliata* (954). The same compound was purified from the ether extract of the Japanese *Jungermannia infusca* (584, 587). The ether extract of *Nardia subclavata* was reinvestigated chemically, resulting in the isolation of the known (–)-kolavelool (**967**) along with some kaurene malonates (1231–1233) (84).



Clerodane-type diterpenoids found in the Marchantiophyta

Liverwort species belonging to the same genus occasionally produce normal and enantiomeric terpenoids, and, sometimes the same species from different localities produces both enantiomers (39, 40, 568). Kolavelool (968) isolated from *Jungermannia infusca* showed a positive optical rotation (600). Its enantiomer, 967, was also isolated from this same liverwort from a different collection location (587). This substance has also been obtained from the higher plant, *Hardwickia pinnata* (547). In order to confirm the absolute configuration of 967, it was oxidized by *t*-BuOOH to give an enone for which the spectroscopic data and X-ray crystallographic analysis results were identical to those of (–)-13-*epi*-2-oxo-kolavelool, a compound of already known absolute configuration, as determined from its ORD and CD spectra, and by X-ray crystallographic analysis (124). Thus, the absolute configuration of (–)-kolavelool (967) was assigned as (5*R*,8*R*,9*S*,10*R*,13*R*) and its enantiomer as *ent*-(13*S*)-hydroxy-3,14-clerodadiene (968) (600). In addition to compound 968, a *cis*-clerodane was isolated from *J. infusca*, with its structure determined as *cis*-3,14-clerodadien-13-ol (969) from the HMBC, HMQC, and NOESY spectra (600).

Kolavenol (970) was isolated from *Jungermannia hyalina* (580) and *Pallavicinia subciliata* (702). Asakawa and Inoue documented that *Adelanthus lindenbergianus* produces an unidentified diterpene-like compound with a molecular weight of 344 (57). Further investigation of the methanol extract of a Patagonian collection resulted in the isolation of the ten new clerodanes 971, 975, and 977–984a, along with the three known clerodanes, *ent*-*cis*-kolavelool (969), anastreptin (973), and orcadensin (974) (116). These three known substances were isolated from the liverwort *Anastrepta orcadensis* (39, 40). The stereochemistry of all of the isolated compounds was settled using a combination of 2D-NMR spectroscopic methods. Compound 969 is of the *ent*-clerodane series and the epimer of the *trans*-clerodane, kolavelool, which was isolated from the liverworts *Jungermannia paroica* and *J. infusca* (40, 600). Compound 975 is of the gymnocolin (976) series and has been isolated from the liverwort *Gymnocolea inflata* (40, 882).

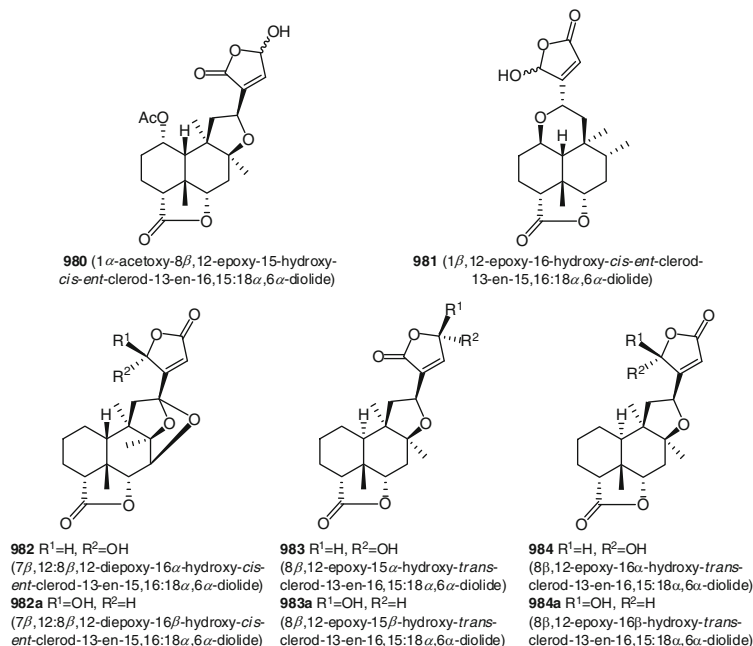


The ether extract of *Heteroscyphus coalitus* was fractionated to give 15-hydroxycleroda-3,(13*E*)-dien-20-oic acid (**972**), the precursor of junceic acid (**972a**), which was found in the same species (**617**).

The Madagascan *Thysananthus spathulistipus* elaborates 3 β ,4 β :15,16-diepoxy-13(16),14-clerodadiene (**985**), and a new clerodane, thysaspathone (**986**) (**294**). The enantiomer of compound **985** has already been isolated from the higher plant *Solidago serotina* (**534**). The structure of **986** was established as 3 β ,4 β :15,16-diepoxy-13(16),14-clerodadiene-7-one from its 2D-NMR and CD spectra.

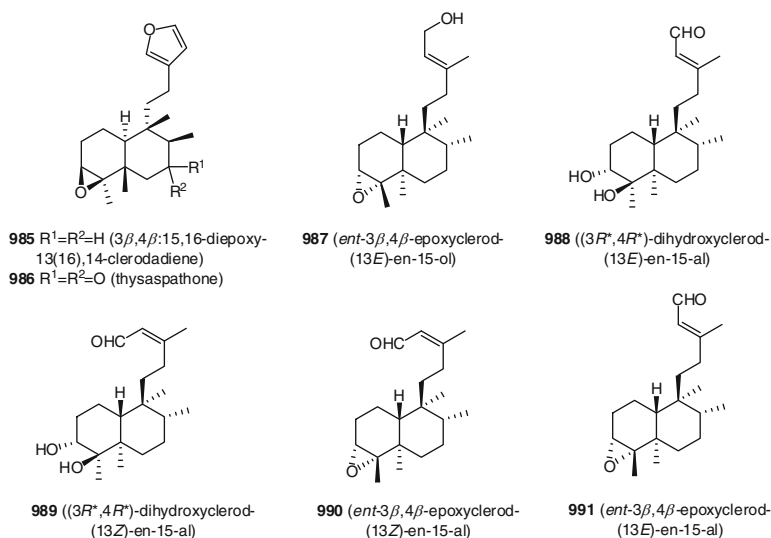
The ether extract of the German *Jungermannia hyalina* was fractionated by HPLC to afford three the new clerodanes **987–989** and a new halimane diterpenoid **1126**, together with *ent*-3 β ,4 β -epoxyclerod-(13*Z*)-*en*-15-al (**990**), *ent*-3 β ,4 β -epoxyclerod-(13*E*)-*en*-15-al (**991**), and kolavenol (**970**) (**580**). The structure of **987** was deduced as 3 β ,4 β -epoxyclerod-(13*E*)-*en*-15-ol by comparison of its spectroscopic data with those of **991**. Reduction of **991** with LiAlH₄ gave a mono alcohol for which the spectroscopic data were identical with those of **987**. The stereostructure of **988** was assigned as (3*R**,4*R**)-dihydroxyclerod-(13*E*)-*en*-15-al, by comparison of its spectroscopic data with those of **991** and from COSY, HMQC, and NOESY experiments. The ¹³C NMR spectrum of **989** was almost identical to that of **988**, indicating that **989** might be the geometrical isomer at C-13/C-14 of **988**. This assumption was confirmed by the presence of a NOE between C-13 Me and H-14. Compounds **970**, **990**, and **991** have been found in *J. paroica* (**40**), which is similar morphologically to *J. hyalina* (**580**).

The New Zealand *Schistochila nobilis* is known to produce schistochilic acids A-C (**992**, **993**, **995**). Further fractionation of the ether extract of the same liverwort led to the isolation of compounds **992** and **993** as well as dehydroschistochilic acid B (**994**) (**635**), which has been isolated from the higher plant, *Haplopappus angustifolius* (**757**). In addition, the *seco*-clerodane, strictic acid (**996**), and (–)-*epi*-hardwickiic acid (**1042**), 5-*epi*-nidoresedic acid (**1044**), and (–)-15,16-epoxy-*cis*-cleroda-3,13(16),14-trien-18,6 α -olide (**1048**) were isolated from the same liverwort. Compound **1044** is the epimer of the already known nidoresedic acid (**640**). Compounds **1042** and **1048** are enantiomers of 5-*epi*-hardwickiic acid (**979**) and (+)-15,16-epoxy-*cis*-cleroda-3,13(16),14-trien-18-oic acid-18,6 α -olide (**535**). All of these structures were elucidated from a combination of ¹H-¹H, ¹H-¹³C COSY, DEPT, HMQC, and HMBC NMR spectroscopic data. The stereochemistry of the *cis*-junction of rings A and B was proven by a NOESY experiment.



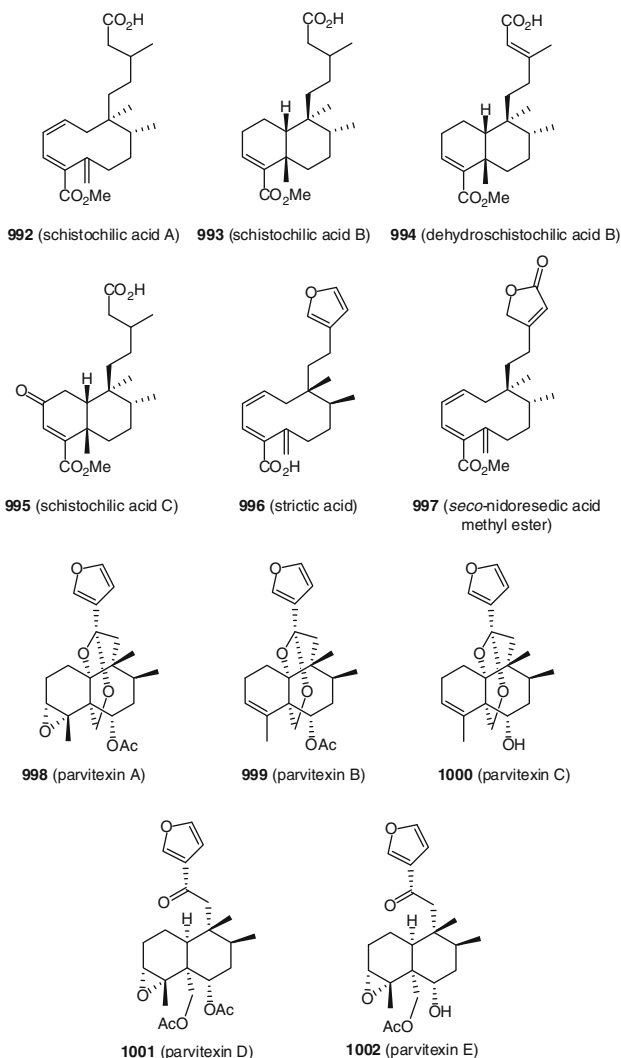
Clerodane-type diterpenoids found in the Marchantiophyta

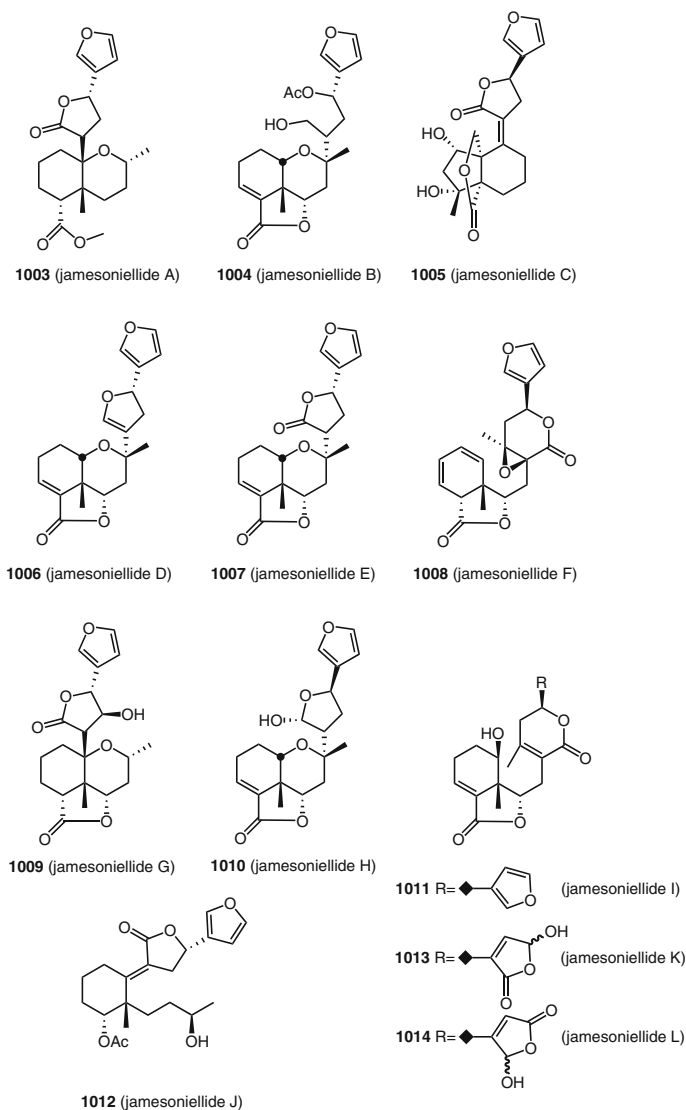
The German *Scapania nemorea* produces *seco*-clerodane acid methyl ester (**997**) ([569](#)), for which the spectroscopic data were identical with those of the methyl ester of *seco*-nidoresedic acid (**759**). The similar *seco*-clerodane, strictic acid (**996**), was isolated from an axenic culture of the same species ([253](#)).



Clerodane-type diterpenoids found in the Marchantiophyta

Five new clerodanes, parvitexins A-E (**998–1003**) were isolated from the *in vitro*-cultured *Scapania parvixesta* and their structures were deduced as 6 α -acetoxy-15,16-epoxycleroda-13(16),14-dien-12,10 α ,19-acetal (**998**), 6 α -acetoxy-3 α ,4 α ,15,16-diepoxycleroda-3,4,13(16),14-trien-12,10 α ,19-acetal (**999**), 15,16-epoxy-6 α -hydroxycleroda-3,4,13(16),14-trien-12,10 α ,19-acetal (**1000**), 6 α ,19-diacetoxy-3 α ,4 α ,15,16-diepoxy-12-oxocleroda-13(16),14-diene (**1001**), and 19-acetoxy-3 α ,4 α ,15,16-diepoxy-6 α -hydroxy-12-oxocleroda-13(16),14-diene (**1002**), by analysis of their 2D-NMR spectra (COSY, COLOC, HSQC, HMBC, NOESY). The absolute configuration of parvitexin C (**1000**) was determined by the modified Mosher method (393). Many furanoclerodanes have been isolated from liverworts (40). These diterpenoids possess an unusual 2,6-dioxabicyclo[3.2.1]octane moiety and are the first natural products having such a structural unit.

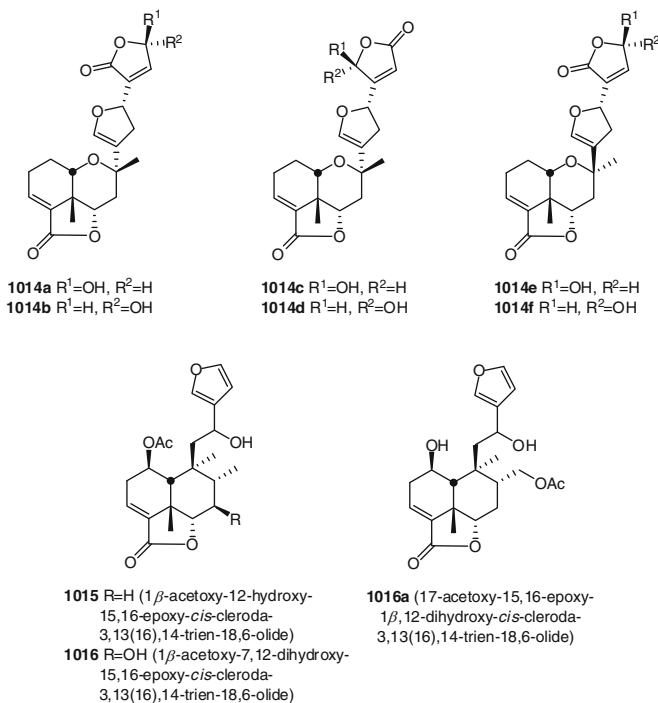




Clerodane-type diterpenoids found in the Marchantiophyta

Jamesoniella species are chemically very complex. They produce kauranes, clerodanes, labdanes, 9,10-*seco*-clerodanes, 13-*epi*-neoverrucosanes, and 13-*epi*-neohomoverrucosanes. *Jamesoniella autumnalis* is one of the most potently bitter-tasting liverworts in the Marchantiophyta. It is also a very rich source of highly oxygenated clerodane and labdane diterpenoids (40). Further fractionation of a crude extract of *J. autumnalis* resulted in the isolation of a new rearranged clerodane named jamesoniellide C (1005). The pentacyclic skeleton was deduced by analysis of a combination of ^1H and ^{13}C NMR and HR-CI mass spectrometric data. Its gross structure was arrived at by 2D-NMR analysis and the complete

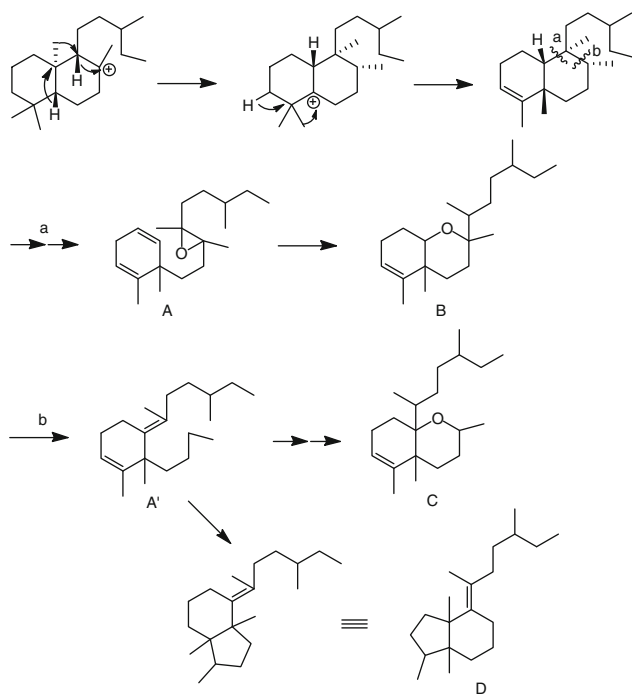
structure was established from its X-ray crystallographic data (808). The ether extract of *Jamesoniella autumnalis* was fractionated by ion-exchange CC and passage over Sephadex LH-20, to afford the nine new clerodanes **1006–1009**, **1014a–1014f**, **1015**, and **1021**, together with the three known clerodanes **1003–1005** (118, 808). The ether extract of the *in vitro*-cultured *J. autumnalis* also produces diterpenoids from the *seco*-clerodane series, jamesoniellides H (**1010**), I (**1011**), and J (**1012**) (817).



Clerodane-type diterpenoids found in the Marchantiophyta

The structure of jamesoniellide D (**1006**) was deduced by analysis of the ^{13}C NMR spectra and comparison of its COSY spectra with jamesoniellide B (**1004**). The relative configuration of **1006** was based on a NOE difference measurement. The structure of jamesoniellide E (**1007**) was assigned readily by the presence of a γ -lactone ring (δ_C 174.8 ppm), in place of the dihydrofuran moiety in jamesoniellide D (**1006**). The structures of jamesoniellide F (**1008**), jamesoniellide G (**1009**), and 1 β -acetoxy-12-hydroxy-15,16-epoxy-*cis*-cleroda-1,13(16),14-trien-18,16-olide (**1015**), were also assigned by the same methods as described above. The formerly assigned structure **1016a**, isolated from the same liverwort (118), should be revised to **1017**. The absolute configurations of all of these new clerodanes remain to be clarified (811).

The structures of **1010–1012** were elucidated by comparison of their NMR spectra of those of jamesoniellide E (**1007**), inclusive of the use of the NOESY, COLOC, and difference NOE pulse sequences (817). The absolute configurations



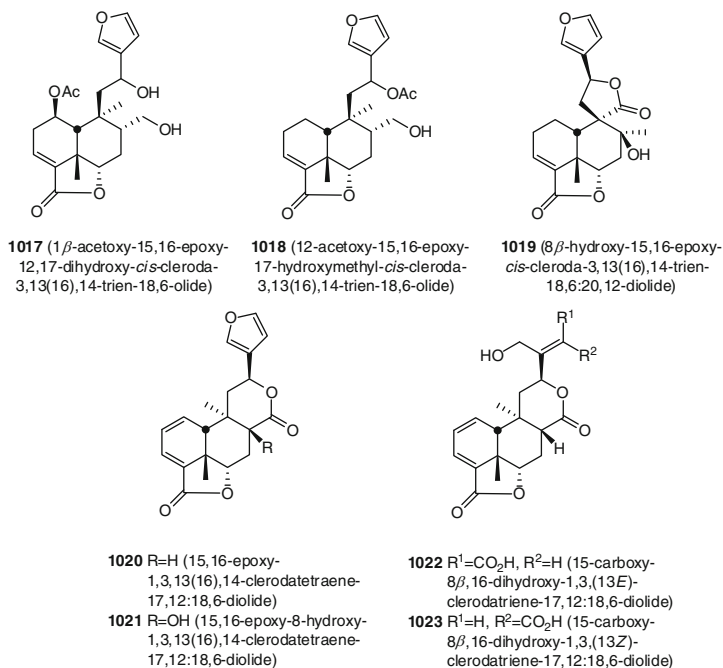
Scheme 4.35 Possible biogenesis pathways for clerodane-type diterpenoids (A, A', B-D) found in *Jamesoniella autumnalis*

of compounds **1010–1012** were determined by application of proton chemical shift differences defined as $\Delta\delta = \delta(S) - \delta(R)$ of their mandelic acid esters (461, 903).

The diterpenoid pattern of *Jamesoniella autumnalis* is almost identical with that found in its *in vitro*-cultured cells. On the basis of the isolated compounds from *J. autumnalis*, possible biosynthesis pathways can be proposed (Scheme 4.35) (811).

The ethyl acetate-soluble part of the methanol extract of *J. colorata* was fractionated to afford two new clerodanes, named jamesoniellides K (**1013**) and L (**1014**), which were obtained along with the known jamesoniellide I (**1011**) (817). The structures of both new clerodanes were confirmed from their 2D-NMR spectroscopic data and by comparison of their NMR spectra with those of other clerodanes found previously (340).

Three epimeric mixtures of clerodanes **1014a/1014b**, **1014c/1014d**, and **1014e/1014f** could not be separated even by HPLC. ^1H COSY and NOE spectroscopic evidence confirmed the presence of the C-16/C-15- γ -butenolide moiety in a mixture of **1014a** and **1014b**. The ^1H and ^{13}C NMR spectra of **1014c** and **1014d** were very similar to those of **1014a** and **1014b**, except that the H-14 resonance was shifted to higher field (δ_{H} 6.02 ppm), suggesting the presence of a 16-hydroxy-13-en-15,16-olide moiety, as found in **1014a** and **1014b**. Compounds **1014e** and **1014f** were found to be the stereoisomers of **1014a** and **1014b**. NOE experiments showed that **1014e** and **1014f** possess an α -orientation of the C-17 methyl group (811).



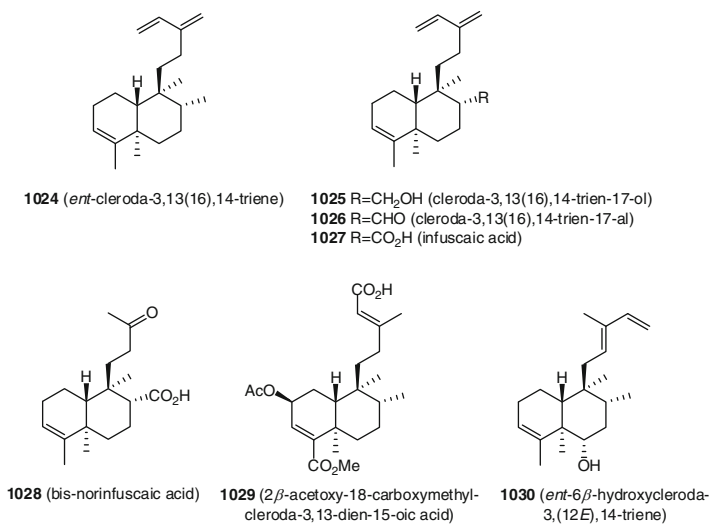
Clerodane-type diterpenoids found in the Marchantiophyta

The clerodane **1021** was assigned as a pentacyclic diterpenoid having a γ - and δ -lactone and a tertiary hydroxy group. The complete structure of **1021** was deduced as 15,16-epoxy-8-hydroxy-1,3,13(16),14-clerodatetraene-17,12:18,6-diolide, by COSY and NOE NMR experiments (811).

The six clerodanes **1016–1023** were isolated from an ether extract of *in vitro*-cultured *Jamesoniella autumnalis* (815). The structure, 1 β -acetoxy-7,12-dihydroxy-15,16-epoxy-*cis*-cleroda-3,13(16),14-trien-18,6-olide for compound **1016** was arrived at as the C-7 β -hydroxy derivative of **1015**, by analysis of its ¹H and ¹³C NMR spectroscopic data, and its complete structure was elucidated using COSY and NOESY experiments. The structure, 12-acetoxy-15,16-epoxy-17-hydroxymethyl-*cis*-cleroda-3,13(16),14-trien-18,6-olide (**1018**), was deduced by comparison with the ¹H NMR spectroscopic data of those of the known compound **1015** (811) and from COSY and NOESY experiments. The structure of the spiro-lactone **1019** was assigned as 8 β -hydroxy-15,16-epoxy-*cis*-cleroda-3,13(16),14-trien-18,6:20,12-diolide, through the use of 2D-NMR (COSY, COLOC, and NOESY) experiments. Comparison of the ¹³C NMR spectrum of **1020** with that of the known compound **1021** confirmed that the former diterpenoid is 15,16-epoxy-1,3,13(16),14-clerodatetraene-17,12:18,6-diolide (811). The NMR spectra of **1022** were very similar to those of **1021** except for the absence of signals for a furan ring. The presence of a 15-carboxy-16-hydroxy-13-ene moiety was confirmed by COSY and NOESY experiments. Thus, the structure of **1022** was established as 15-carboxy-8 β ,16-dihydroxy-1,3,(13*E*)-clerodatriene-17,12:18,6-diolide. The NMR data of **1023** closely resembled those of **1022** except that the H-12, H-14, H-16,

and H-16' resonances were shifted to lower fields, indicating these compounds to be diastereomers at C-13/C-14. The observation of NOE cross peaks between H-12 and H-14 in **1022** and H-14 and H-16 showed the double bond as (13*E*) in **1022** and (13*Z*) in **1023**. Consequently, the structure of **1023** was deduced as being 15-carboxy-8 β ,16-dihydroxy-1,3,(13*Z*)-clerodatriene-17,12:18,6-diolide (**815**).

The two new clerodanes **1024** and **1025**, and the new bis-*nor*-clerodane **1028**, were isolated from the ether extract of *Jungermannia infusca*, together with the six known clerodanes **1026**, **1027**, **1033**, **1034**, **1038**, and **1039** (**592**). The similarity of the spectroscopic data of **1024** with those of **1026**, **1027**, **1034**, **1038**, and **1039** suggested that **1024** possesses the same clerodane skeleton. This assumption was confirmed by the analysis of the COSY, HMQC, and HMBC spectra. Conclusive evidence for the absolute stereostructure was obtained by the formation of **1024** from **1026**. Reduction of **1026** with LiAlH₄, followed by tosylation and further reduction furnished *ent*-cleroda-3,13(16),14-triene (**1024**). Compound **1025** was assigned as *ent*-clerod-3,13(16),14-trien-17-ol, since the spectroscopic data of **1025** were identical with those of the hydrogenated product from **1026** and **1027**. The structure of bis-*nor*-infuscaic acid (**1028**) was established by a combination of determination of the molecular formula as C₁₈H₂₈O₃, the formation of a methyl ester, and analysis of the COSY, HMQC, HMBC, and NOESY spectra.



Clerodane-type diterpenoids found in the Marchantiophyta

A new clerodane diterpenoid, 2 β -acetoxy-18-carboxymethylcleroda-3,13-dien-15-oic acid (**1029**), was isolated from the ether extract of the Japanese *Scapania bolanderi* (**818**). Fractionation of the ether extract of the New Zealand *Heteroscyphus billardieri* led to the isolation of the three new *ent*-clerodanes, *ent*-6 β -hydroxycleroda-3,(12*E*),14-triene (**1030**), *ent*-2 β -hydroxycleroda-3,(12*E*),14-triene (**1031**), and 4,13-dihydroxyclerod-14-ene (**1032**). The stereostructures of all these compounds were elucidated using their 2D-NMR spectroscopic data. The absolute structure of

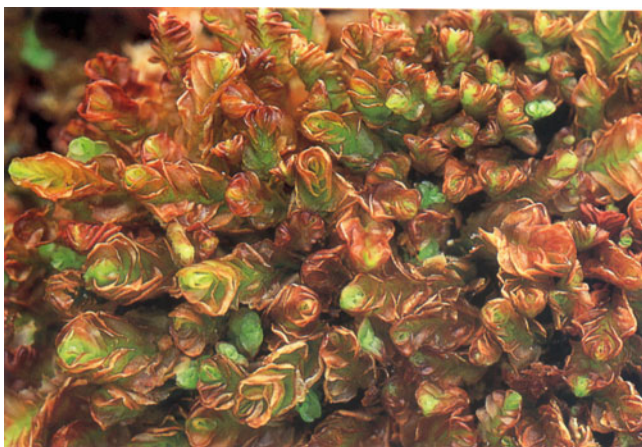


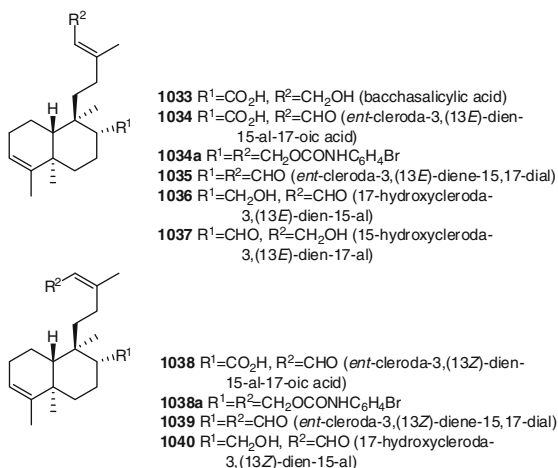
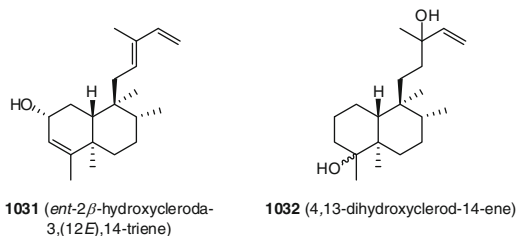
Fig. 4.16 *Jungermannia infusca*. (Permission for the use of this figure has been obtained from Mr. Masana Izawa, Saitama, Japan)

1030 was determined by a positive and a negative *Cotton* effect at 253.5 nm and 232.2 nm in the CD spectrum of the *ent*-6 β -benzoate of **1030**. The absolute configuration of **1031** was also deduced from a positive *Cotton* effect at 245 nm of the *p*-bromobenzoate of **1031**. Compound **1032** possesses the same skeleton as that of **1030** and **1031**. The position of two hydroxy groups was confirmed by comparison of its spectroscopic data with those of **1030** and **1031**, but, however, the relative configurations of the two alcohol groups present remained to be established (607, 635).

Jungermannia infusca (Fig. 4.16) is polymorphic and its chemical constituents are dependent on the collection site (568). The Japanese *Jungermannia infusca* elaborates compound **1033**. Its structure was proved to be bacchasalicylic acid, previously isolated from *Baccharis* species (Compositae) (977), because the spectroscopic data of the methyl ester of **1033** were identical with those of methyl bacchasalicylate. Compounds **1034** and **1038**, (13*E*)-symphyoreticulic acid and (13*Z*)-symphyoreticulic acid, were isolated from *J. infusca* collected from a different locality), and their relative configuration was established by complete assignment of their ^1H and ^{13}C NMR spectra (862). In order to establish their absolute configuration, an X-ray crystallographic analysis of the carbamate of **1034** was carried out. Reduction of a mixture of **1034** and **1038** with LiAlH_4 , followed by reaction with 4-bromophenyl isocyanate, furnished the carbamates **1034a** and **1038a**, which were purified by CC. The X-ray crystallographic determination of **1034a** confirmed that **1034** is of the *ent*-clerodane series and its diastereomer **1038** was proposed to have the same configuration (592). Compound **1035** was previously isolated from the same liverwort (862), together with **1034**, **1038**, and **1039**. The spectroscopic data of the diol derivative of **1035** were identical with those of the diol derived from **1035**. Thus, compound **1035** and its diastereomer **1039** possess the same absolute configuration as **1034** (597).

Further fractionation of the ether extract of *J. infusca*, collected at Ehime in Japan, resulted in the isolation of the three new clerodanes infuscolide A (**1041**), 17-hydroxy-

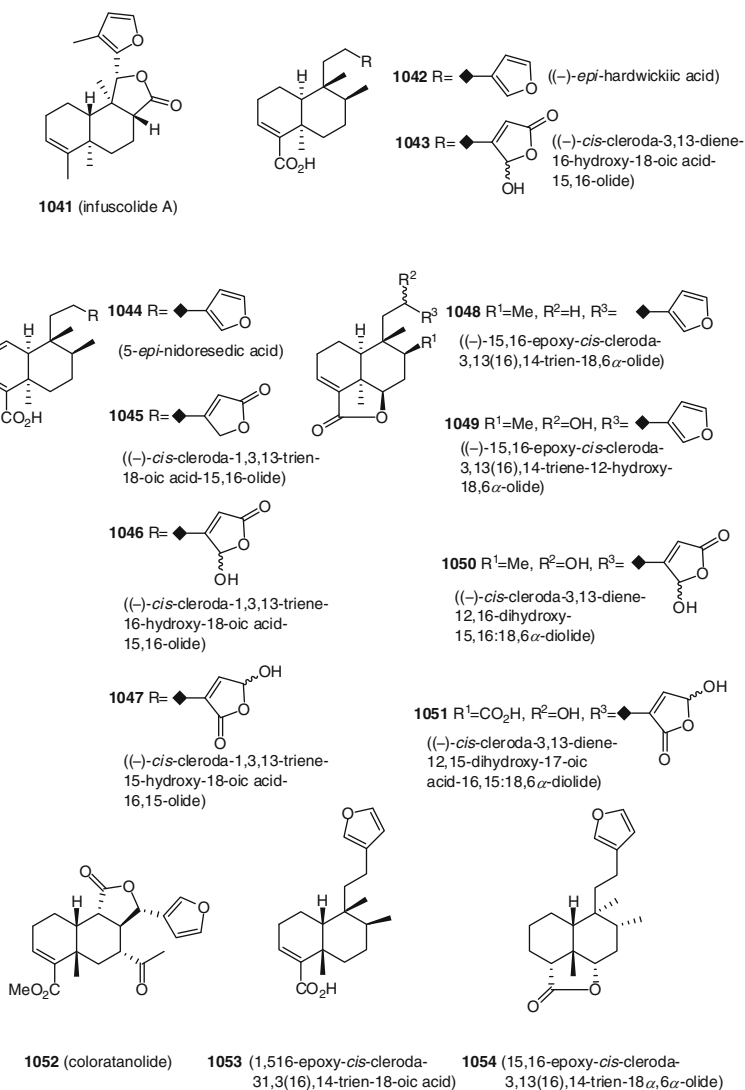
3,(13*E*)-clerodadien-15-al (**1036**), and 17-hydroxy-3,(13*Z*)-clerodadien-15-al (**1040**). The complete structure of **1041** was elaborated from 2D-NMR spectroscopic data, and an X-ray crystallographic analysis established the stereostructure to be 12,15-epoxy-3,12,14-clerodatrien-17,11-olide. Compounds **1036** and **1040** showed very similar NMR spectra to those of **1037**, indicating these compounds to be stereoisomers. Conclusive evidence for these structures was obtained by measuring the NOESY spectra for both compounds. The absolute configurations of **1036**, **1040**, and **1041** are the same as that of **1034**, for which the carbamate structure was determined by X-ray crystallographic analysis. In addition, the nine known clerodanes, cleroda-3,13(16),14-triene (**1024**), cleroda-3,13-(16),14-trien-17-al (**1026**), infuscaic acid (**1027**), cleroda-3,13(16),14-trien-17-ol (**1025**), cleroda-3,(13*E*)-dien-15-al-17-oic acid (**1034**), cleroda-3,(13*E*)-diene-15,17-dial (**1035**), cleroda-3,(13*Z*)-dien-15-al-17-oic acid (**1038**), cleroda-3,(13*Z*)-diene-15,17-dial (**1039**), and 15-hydroxy-3,(13*E*)-clerodadien-17-al (**1037**), were isolated (597).



Clerodane-type diterpenoids found in the Marchantiophyta

Scapania species are rich sources of both sesquiterpenoids and diterpenoids. *Scapania nemorea* is widespread in countries of the Northern Hemisphere. The ether- and ethyl acetate-soluble partitions of the methanol extract of *S. nemorea* led to the isolation of the seven *cis*-clerodanes, (–)-*cis*-cleroda-3,13-diene-16-hydroxy-18-oic acid-15,16-olide (**1043**), (–)-*cis*-cleroda-1,3,13-trien-18-oic acid-15,16-olide (**1045**), (–)-*cis*-cleroda-1,3,13-triene-16-hydroxy-18-oic acid-15,16-olide (**1046**), (–)-*cis*-cleroda-1,3,13-triene-15-hydroxy-18-oic acid-16,15-olide (**1047**), (–)-15,16-epoxy-*cis*-cleroda-3,13(16),14-triene-12-hydroxy-18,

6 α -olide (**1049**), (–)-*cis*-cleroda-3,13-diene-12,16-dihydroxy-15,16:18,6 α -diolide (**1050**), and (–)-*cis*-cleroda-1,13-diene-12,15-dihydroxy-17-oic acid-16,15:18,6 α -diolide (**1051**). In addition, the *seco*-clerodane, strictic acid (**996**), (–)-*epi*-hardwickiic acid (**1042**), 5-*epi*-nidoresedic acid (**1044**), and (–)-15,16-epoxy-*cis*-cleroda-3,13(16),14-trien-18,6 α -olide (**1048**), were also isolated from the same liverwort (**253**). Compound **1044** is the epimer of the already known nidoresedic acid (**640**). Compounds **1042** and **1048** are enantiomers of 5-*epi*-hardwickiic acid (**979**) and (+)-15,16-epoxy-*cis*-cleroda-3,13(16),14-trien-18-oic acid-18,6 α -olide (**535**). All of these structures were elucidated using a combination of their ^1H - ^1H , and ^1H - ^{13}C COSY, DEPT, HMQC, and HMBC NMR spectroscopic data. The stereochemistry of the *cis*-junction of rings A and B was proven by a NOESY experiment (**253**).

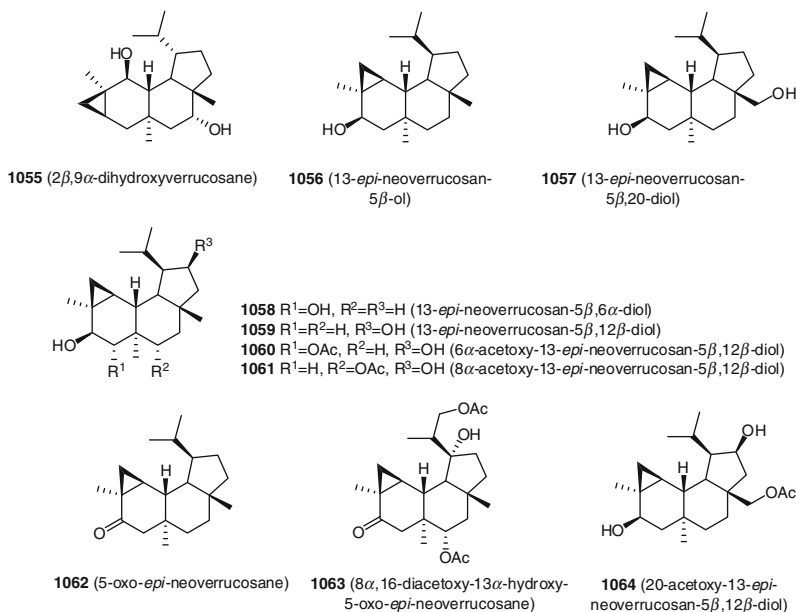


The ether extract of the New Zealand *J. colorata* was purified by CC to give a new rearranged clerodane named coloratanolide (**1052**). The complete structure of **1052** was assigned by a combination of 1D- and 2D-NMR (HMQC, HMBC, and NOESY) methods (635, 901).

Diplophyllum albicans and *D. serrulatum* are rich sources of eudesmanolides and drimane sesquiterpenoids (40). *D. plicatum* is chemically different from these two species since it elaborates the two clerodanes 15,16-epoxy-*cis*-cleroda-3,13(16),14-trien-18-oic acid (**1053**) and 15,16-epoxy-*cis*-cleroda-3(16),14-dien-18 α ,6 α -olide (**1054**), both bearing a β -furan ring (84).

4.3.3 Cyathanes

The cyathane diterpenoids are relatively rare in Nature. Certain *Plagiochila*, *Jamesoniella* (Jungermanniales), and *Fossombronia* (Metzgeriales) species are rich sources of cyathane diterpenoids.



Cyathane-type diterpenoids found in the Marchantiophyta

Ludwiczuk and colleagues identified the presence of 2 β ,9 α -dihydroxyverrucosane (**1055**) in the ether extract of the Greek *Fossombronia angulosa* (492). From the ether extract of the Chilean *Lepicolea ochroleuca*, 13-*epi*-neoverrucosan-5 β -ol (**1056**) was identified, together with a number of aromadendrane sesquiterpenoids (478). Compound **1056** was found in the different liverworts *Plagiochila*

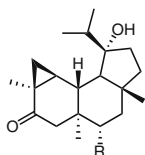
stephensoniana, *Schistochila nobilis* (40, 635), *Heteroscyphus planus* (310), *Fossombronia alaskana* (269), *Plagiochila circinalis*, and *Dendromastigophora flagellifera* (635). This is the first *epi*-neohomoverrucosane diterpenoid to have been isolated from the liverworts.

The ether extract of *Heteroscyphus planus* was fractionated to give a new neoverrucosane, 13-*epi*-neoverrucosan-5 β ,20-diol (**1057**), together with 13-*epi*-neoverrucosan-5 β -ol (**1056**). The signal patterns of the ^1H NMR spectrum of **1057** were very similar to those of the known compound **1056** except for the presence of primary hydroxy groups, indicating that **1057** is a 13-*epi*-neoverrucosane with a 5 β -hydroxy group and a primary alcohol group at C-10, C-15, or C-20. This assumption was confirmed by chemical transformation of **1057**. Tosylation of **1057** gave a monotosylate, which was reduced with Zn-NaI to afford 13-*epi*-neoverrucosane (**1056**). The location of the primary alcohol at C-20 was confirmed by a NOESY experiment (310). The same compound (**1057**) and 13-*epi*-homoverrucosan-5 β -ol (**1073**) (40) were isolated from the ether extract of *Plagiochila circinalis* (635).

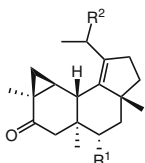
The dichloromethane extract of the South American *Plagiochila dusenii* was purified by CC to give the four verrucosanes **1059**, and **1060**, **1061**, and **1071** (32), together with 13-*epi*-neoverrucosan-5 β -ol (**1056**) (40). 13-*epi*-Neoverrucosan-5 β ,12 β -diol was proposed as having the structure **1059** by comparison of its spectroscopic data with those of 13-*epi*-neoverrucosan-5 β ,20-diol (**1057**) and 13-*epi*-homoverrucosan-5 β -ol (**1073**) (40). 13-*epi*-Neoverrucosan-8 α -acetoxy-5 β ,12 β -diol was determined as having the structure **1061** by ^1H - ^1H , ^1H - ^{13}C COSY (HSQC), and ^{13}C - ^1H long range COSY (HMBC) spectroscopic analysis. The structure of **1060** was deduced as 13-*epi*-neoverrucosan-6 α -acetoxy-5 β ,12 β -diol by comparison of its NMR spectroscopic data with those of **1061** and from a NOESY experiment. The similarity of the NMR spectra of **1059** with those of **1056**, **1060**, and **1061** and 20-acetoxy-13-*epi*-neoverrucosan-5 β ,12 β -diol (**1064**) (872), and the absence of an acetoxy group in the molecule, led to the structure proposed (32).

An *in vitro*-culture of *Fossombronia alaskana* was extracted with ether, followed by chromatography, to afford the five new *epi*-verrucosanes, 5-oxo-*epi*-neoverrucosane (**1062**), 8 α ,16-diacetoxy-13 α -hydroxy-5-oxo-*epi*-neoverrucosane (**1063**), 13 α -hydroxy-5-oxo-*epi*-neoverrucosane (**1065**), 8 α -acetoxy-13 α -hydroxy-5-oxo-*epi*-neoverrucosane (**1066**), and 8 α ,13 α -dihydroxy-5-oxo-*epi*-neoverrucosane (**1067**) (269), together with the known 5 β -hydroxy-13-*epi*-neoverrucosane (**1056**) (40). Compound **1062** is the dihydro derivative of the known compound **1056** and the stereostructure was established from its X-ray crystallographic analysis. The structures of the other compounds were based on a combination of chemical reaction, 2D-NMR analysis, and comparison of their spectroscopic data with those of compound **1062**. Dehydration of compound **1063** gave 8 α ,16-diacetoxy-5-oxoneoverrucos-13-ene (**1067a**). The *epi*-homoverrucosane derivative **1071** was

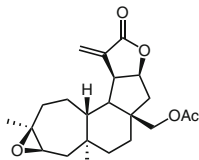
concluded to be a natural product since no homoallylic ring expansion of **1066** occurred when this compound was reacted with 0.5 *N* sulfuric acid under reflux for 5 h. Instead of the formation of *epi*-homoverrucosane, the two dehydrated *epi*-neoverrucosanes, **1067b** and **1067c**, were obtained (269).



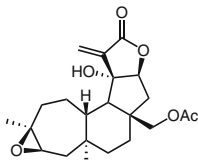
1065 R=H (13 α -hydroxy-5-oxo-*epi*-neoverrucosane)
1066 R=OAc (8 α -acetoxy-13 α -hydroxy-5-oxo-*epi*-neoverrucosane)
1067 R=OH (8 α ,13 α -dihydroxy-5-oxo-*epi*-neoverrucosane)



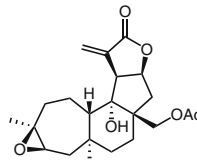
1067a R¹=OAc, R²=CH₂OAc (8 α ,16-diacetoxy-5-oxo-neoverrucos-13-ene)
1067b R¹=OAc, R²=Me (8 α -acetoxy-5-oxo-neoverrucos-13-ene)
1067c R¹=OH, R²=Me (8 α -hydroxy-5-oxo-neoverrucos-13-ene)
1067d R¹=H, R²=Me (5-oxo-neoverrucos-13-ene)



1068 (20-acetoxy-4 β ,5 β -epoxy-13-*epi*-neohomoverrucosan-15(17)-en-16,12 β -olide)



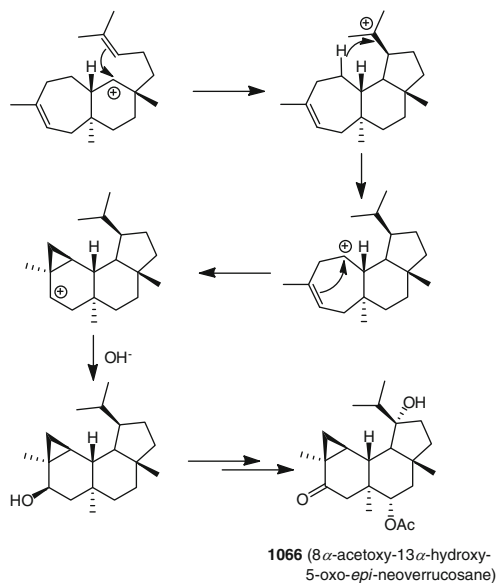
1069 (20-acetoxy-4 β ,5 β -epoxy-13 α -hydroxy-13-*epi*-neohomoverrucosan-15(17)-en-16,12 β -olide)



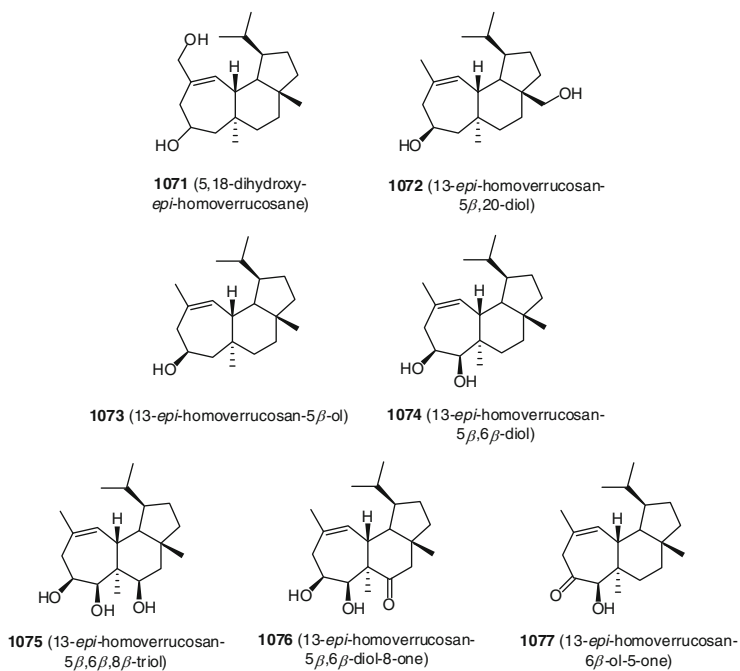
1070 (20-acetoxy-4 β ,5 β -epoxy-14 α -hydroxy-13-*epi*-neohomoverrucosan-15(17)-en-16,12 β -olide)

Cyathane-type diterpenoids found in the Marchantiophyta

An incorporation experiment for 5-oxo-neoverrucos-13-ene (**1067d**) was carried out by addition of [1-¹³C] labeled glucose into axenic cultures of the Arctic *Fossombronia alaskana*. Quantitative ¹³C NMR spectroscopic analysis of the resulting labeled profiles indicated that the isoprene units of **1067d** are derived through the mevalonic pathway (339). The biosynthesis of 8 α -acetoxy-13 α -hydroxy-5-oxo-13-*epi*-neoverrucosane (**1066**), isolated from *Fossombronia alaskana*, was investigated by incorporation experiments using [1-¹³C]- and [U-¹³C₆]glucose as precursors. The data showed conclusively that the C₅ building blocks, isopentenyl pyrophosphate and dimethylallyl pyrophosphate of *epi*-neoverrucosane (**1066**), are biosynthesized predominantly (>95%) *via* the deoxyxylulose pathway (Scheme 4.36). Evidence for an unusual 1,5-hydride shift before the formation of the cyclopropyl moiety in compound **1066** was obtained by an incorporation experiment with [6,6-²H₂]glucose (202). The *epi*-neoverrucosanes found in *Fossombronia alaskana* are biosynthesized *via* the deoxyxylulose pathway (830).



Scheme 4.36 Biosynthesis pathways for *epi*-neoverrucosane



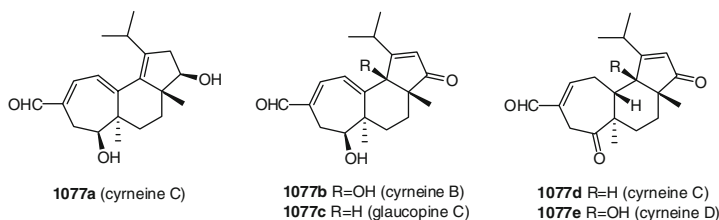
Cyathane-type diterpenoids found in the Marchantiophyta

Jamesoniella autumnalis tastes very bitter. This taste is caused by the presence of highly oxygenated clerodane diterpenoids (40). In contrast, the New Zealand *J. tasmanica* is not bitter at all. Fractionation of the ether extract of *J. tasmanica* led to the isolation of 20-acetoxy-13-*epi*-neoverrucosane-5 β ,12 β -diol (1064), 20-acetoxy-4 β ,5 β -epoxy-13-*epi*-neohomoverrucos-15(17)-en-16,12 β -olide (1068), 20-acetoxy-4 β ,5 β -epoxy-13 α -hydroxy-13-*epi*-neohomoverrucos-15(17)-en-16,12 β -olide (1069), and 20-acetoxy-4 β ,5 β -epoxy-14 α -hydroxy-13-*epi*-neohomoverrucos-15(17)-en-16,12 β -olide (1070), together with the known (+)-13-*epi*-neoverrucosan-5 β -ol (1056). The structures of the new compounds were deduced by 2D-NMR (HMBC, HMQC, NOESY) spectroscopic analysis (872).

The ether extract of Colombian *Plagiochila cristata* was purified by CC to give the four new 13-*epi*-homoverrucosanes, 13-*epi*-homoverrucosan-5 β ,6 β -diol (1074), 13-*epi*-homoverrucosan-5 β ,6 β -diol-8-one (1076), 13-*epi*-homoverrucosan-6 β -ol-5-one (1077), and 13-*epi*-homoverrucosan-5 β ,6 β ,8 β -triol (1075), together with the known 13-*epi*-homoverrucosan-5 β -ol (1073), which was previously isolated from the New Zealand *Schistochila nobilis* (40). Compound 1074 was found to show very similar spectroscopic parameters to compound 1073, except for evidence of the presence of one more secondary hydroxy group. The position of this hydroxy group at C-6 β was confirmed by ^1H - ^1H -COSY and double resonance NMR examination. The configurations at both alcohol groups were established by NOE effects between H-5, H-6, and the C-7 methyl group. The NMR spectra of 1076 resembled those of 1074, except for the presence of a keto group (δ_{C} 216.6 ppm, 1699 cm^{-1}). The position of the keto group at C-8 in 1076 was arrived at by the close examination of the ^1H - ^1H COSY spectrum. The absolute configuration of the two hydroxy groups was confirmed to be the same as those of 1074 because of the presence of the same NOE observations as shown for these two compounds (910). The NMR spectra of 1077 were found to be similar to those of 1074, except for the presence a ketone group, and the absence of the secondary hydroxy group, indicating one of the secondary alcohol functionalities in 1074 to be oxygenated. The location of the ketone group at C-5 was established by the observation of a NOE between H-6 and the tertiary methyl group at C-7. Comparison of the spectroscopic data of 1075 with those of 1074 and COSY experiments suggested that 1075 is the 8-hydroxy derivative of 1074. This assumption was confirmed by X-ray crystallographic analysis of 1075 (910).

Previously, (–)-verrucosan-2 β -ol and neoverrucosane have been found in other organisms, namely, the phototrophic bacterium *Chloroflexus aurantiacus* (329) and an Okinawan sponge (40). Twenty-seven homoverrucosane diterpenoids, possessing growth inhibitory effects for the hepatitis B virus, HIV-1, *Mycobacterium tuberculosis* as well as human primary tumor cells, have been isolated from the Jamaican sponge *Myrmedioderma styx* (648). The mushroom *Sarcodon cyrneus*

elaborates the new cyathane diterpenes cyrneine C (**1077d**) and D (**1077e**), along with cyrneines A (**1077a**) and B (**1077b**), and glaucopine (**1077c**) (505).



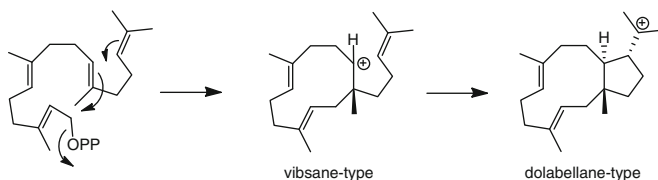
Cyathane-type diterpenoids found in the mushroom *Sarcodon cyrneus*

4.3.4 Dolabellanes

Huneck and associates reported the presence of 18-hydroxydolabell-(7*E*)-en-3-one (**1078**) and 10-deacetoxybarbilycopodin (**1079**) and some related compounds in *Barbilophozia* species (361). The Swiss *Barbilophozia floerkei* and *B. lycopodioides* and the French *B. barbata* elaborate the same compound, **1078** (583). The French and Finnish *B. barbata* also produce the same dolabellane, namely, compound **1079** (596).

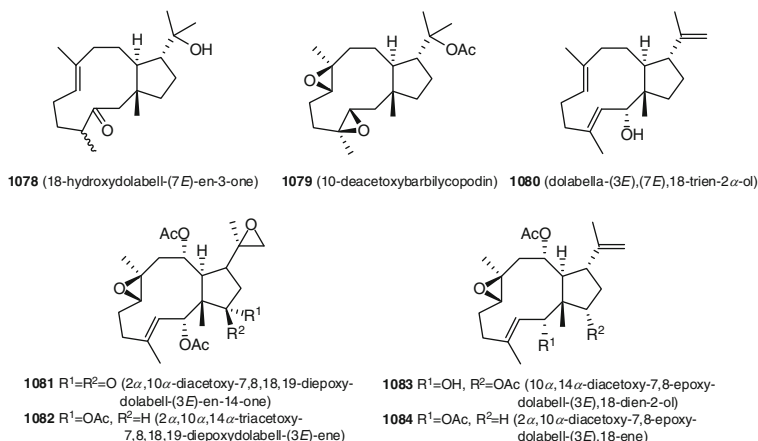
Chandonanthus hirtellus elaborates the cembrane diterpenoids **948**, **949**, **952**, and **953**. Further investigation of the ether extract of the West Malaysian *C. hirtellus* led to the isolation of the five new dolabellane diterpenoids **1080–1084**. The structure of **1081** was established as 2 α ,10 α -diacetoxy-7,8,18,19-diepoxydolabell-(3*E*)-en-14-one by X-ray crystallographic analysis. Comparison of their spectroscopic data revealed that a secondary acetoxy group in **1082** replaces a ketone group in **1081**. This was confirmed by HMBC correlations. Thus, the structure of **1082** was assigned as 2 α ,10 α ,14 α -triacetoxy-7,8,18,19-diepoxydolabell-(3*E*)-ene. The structures of **1080**, **1083**, and **1084** were proposed as dolabella-(3*E*,7*E*),18-trien-2 α -ol, 10 α ,14 α -diacetoxy-7,8-epoxydolabell-(3*E*),18-dien-2 α -ol, and 2 α ,10 α -diacetoxy-7,8-epoxydolabell-(3*E*),18-diene, on the basis of the analysis of their 2D-NMR spectra (927).

The ether extract of the Japanese *Odontoschisma denudatum* was purified by CC to give the known dolabellane acetoxyodontoschismenol (**1085**) (40) and the four new dolabellanes **1086–1089**, of which acetoxyodontoschismenetriol (**1086**) was the major component, along with denudatenone diterpenoids (see Sect. 4.3.16). The structure and relative configuration of **1086** was established using a combination of 2D-NMR data interpretation and X-ray crystallographic analysis. The absolute configuration was based on several chemical reactions, the CD spectrum, and the modified Mosher method. Thus, two hydroxy groups at C-10 and C-12 of **1086** were protected as an acetonide, which was reacted with *t*-Bu (Me)₂SiCl and then LiAlH₄ to furnish the 6-hydroxy product. This was followed by treatment with *p*-bromobenzoic acid to afford the monobromobenzoate,



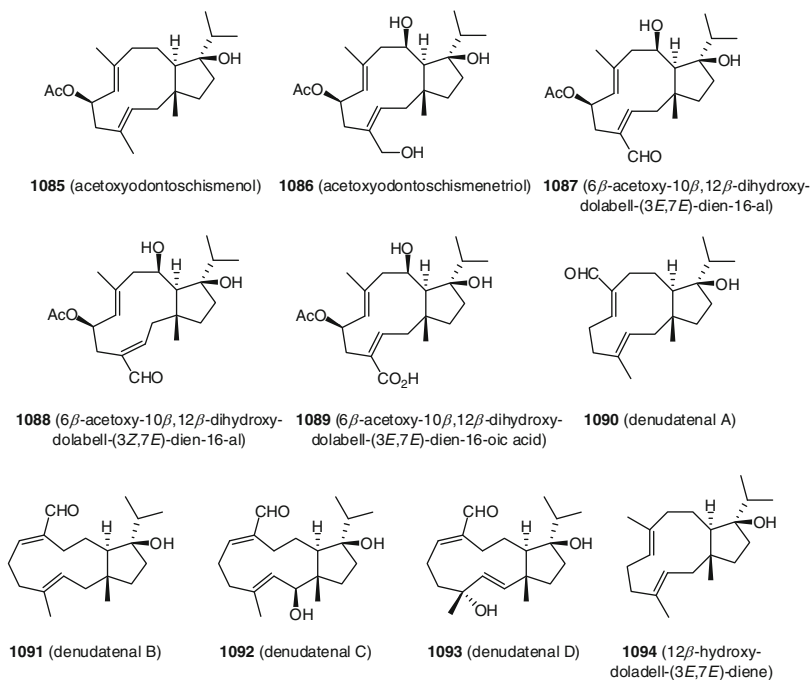
Scheme 4.37 Possible biogenesis pathway for dolabellane-type diterpenoids

which showed a negative *Cotton* effect at 241 nm. The modified *Mosher* method was used to demonstrate that the absolute configuration at C-6 is (*R*). Thus, the structure of **1086** was established as (1*R*,6*R*,10*R*,11*S*,12*R*)-6-acetoxy-10,12,16-trihydroxydolabella-(3*Z*,7*E*)-diene.



Dolabellane-type diterpenoids found in the Marchantiophyta

The structures of the other dolabellanes **1087–1089** were established by comparison of their spectroscopic data with those of compounds **1085** and **1086** (316, 319). Further fractionation of the ether extracts of *Odontoschisma denudatum* and *Plagiochila sciophila* resulted in the isolation of four new dolabellanes, named denudatenals A-D (**1090–1093**) and the new 12 β -hydroxydolabella-(3*E*,7*E*)-diene (**1094**). Their structures were elucidated by 2D-NMR analysis (326). Dolabellanes might be biosynthesized *via* vibansane diterpenoids co-occurring in the same liverwort, as shown in Scheme 4.37.



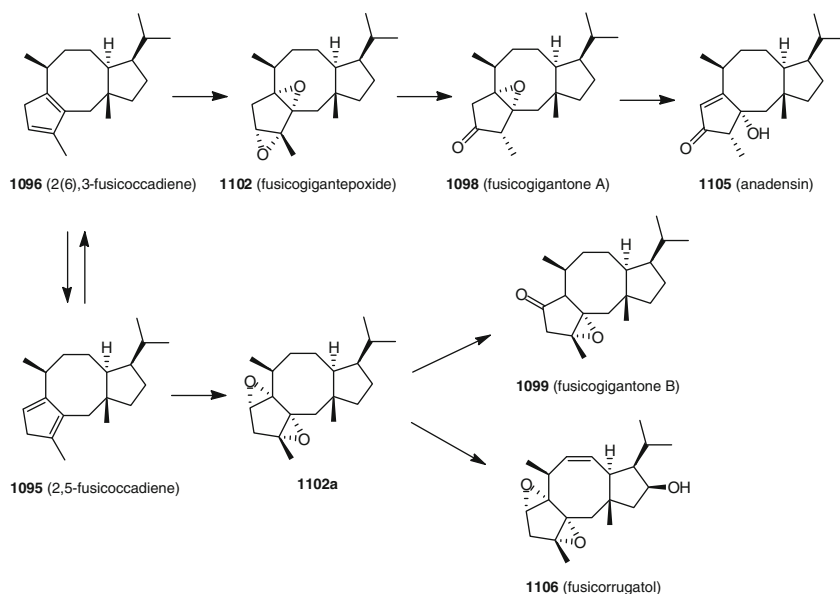
Dolabellane-type diterpenoids found in the Marchantiophyta

4.3.5 Fusicoccanes

Many highly oxygenated fusicoccanes have been isolated from liquid culture filtrates of the canola pathogen *Altenaria brassicicola* (499). Fusicoccanes are relatively widely distributed in *Plagiochila* and *Frullania* species. One of the most common fusicoccanes found in these liverworts is 2,5-fusicoccadiene (1095), as shown in Table 4.3. The double bond isomers 1096 and 1097 of 1095 have been detected in *Frullania patula* (78) and *Chandonanthus hirtellus* and an unidentified *Frullania* species (423, 494). *Plagiochila aerea* was extracted with deuteriochloroform, and the ^1H NMR spectrum of the crude extract indicated the presence of fusicoccadiene (1095) (334). Further investigation of the essential oil of *Lophozia ventricosa* resulted in the identification of fusicoccadiene (1095) as a trace constituent (486).

Fusicogigantone A (1098) and fusicogigantenone B (1099) have been isolated from *Plagiochila corrugata* and *Pleurozia gigantea* (40). The same compounds are also constituents not only of *Frullania hamatiloba* (316) and *Plagiochila adianthoides*, *P. cristata*, *P. dusenii*, and *P. yokogurensis* (32, 84, 910), but also of *Anastrophyllum auritum* (976) *Lepicolea ochroleuca* (478), and *Chandonanthus hirtellus* (423, 490).

A new fusicoccane, 3 α -hydroxyfusicocc-2(6)-en-5-one (1100), was isolated from the ether extract of the Scottish *Plagiochila spinulosa* together with



Scheme 4.38 Formation of oxygenated fusicoccane-type diterpenoids from fusicoccadienes

spinuloplugin A (**1124**) and spinuloplugin B (**1125**) ([40](#)). Compound **1100** might be biosynthesized from fusicogigantone B (**1099**), found in *Plagiochila sciophila* ([617](#)).

Anton and colleagues reported the isolation of fusicoincurvatone A (**1101**) from the South American *Plagiochila dusenii* ([32](#)). Fusicogigantepoxide (**1102**) has been isolated previously from the Malaysian *Pleurozia gigantea* ([40](#), [65](#)) but its relative configuration was not determined. Compound **1102** was isolated from the Panamanian *Bryopteris filicina* and its relative stereostructure was assigned by X-ray crystallographic analysis ([576](#)).

Further investigation of lipophilic compounds of *Plagiochila asplenioides* ([441](#)), the Costa Rican *Bryopteris filicina* ([604](#)) and the Tahitian *Chandonanthus hirtellus* ([421](#), [423](#)) gave anadensin (**1105**). However, this compound was not detected in a specimen of *B. filicina* collected in Panama ([576](#)).

Previously, the isolation of the new fusicoccane diterpenoid fusicorrugatol (**1106**) has been reported from the Venezuelan *Plagiochila corrugata* ([40](#)). The structure and relative configuration of **1106** were established by its X-ray crystallographic analysis. Fusicogigantepoxide (**1102**) and its isomer **1102a** might be derived from the fusicoccadienes **1095** and **1096** by oxidation *via* endoperoxides and through rearrangement. Anadensin (**1105**) may be derived from fusicogigantone A (**1098**), as shown in Scheme 4.38 ([842](#)).

Fusicogigantones A (**1098**) and B (**1099**) and fusicogigantepoxide (**1102**) were synthesized from fusicocca-2(6),3-diene (**1096**) and fusicocca-2,5-diene (**1095**) by oxidation with singlet oxygen ([394](#)).

Table 4.3 Diterpenoids found in the Marchantiophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
945	Cembrene (= Thunbergene)	$\text{C}_{20}\text{H}_{32}$			<i>Chandonanthus hirtellus</i>	(423)	
946	Cembrene A	$\text{C}_{20}\text{H}_{32}$			<i>Chandonanthus hirtellus</i>	(494)	
947	Cembrene C	$\text{C}_{20}\text{H}_{32}$			Unidentified <i>Jungmannia</i> sp.	(423)	
948	Chandonanthone	$\text{C}_{20}\text{H}_{30}\text{O}_4$			Unidentified <i>Jungmannia</i> sp.	(494)	X-ray
					<i>Chandonanthus hirtellus</i>	(421)	
						(423)	
949	iso-Chandonanthone	$\text{C}_{20}\text{H}_{30}\text{O}_4$			<i>Chandonanthus hirtellus</i>	(494)	
						(748)	X-ray
950	Chandonanthin	$\text{C}_{20}\text{H}_{30}\text{O}_6$			<i>Chandonanthus hirtellus</i>	(490)	
						(748)	
						(421)	
						(423)	
951	iso-Chandonanthin	$\text{C}_{20}\text{H}_{30}\text{O}_6$			<i>Chandonanthus hirtellus</i>	(748)	
952	8,10-Di- <i>epi</i> -chandonanthone	$\text{C}_{20}\text{H}_{30}\text{O}_4$	127-139	+86	<i>Chandonanthus hirtellus</i>	(748)	X-ray
953	β -1,15-Dihydro-8,10-di- <i>epi</i> -chandonanthone	$\text{C}_{20}\text{H}_{32}\text{O}_4$	132-136	-29	<i>Chandonanthus hirtellus</i>	(927)	X-ray
954	13,18,20-tri- <i>epi</i> -iso-Chandonanthone	$\text{C}_{20}\text{H}_{30}\text{O}_4$	141-142	+10.6	<i>Chandonanthus hirtellus</i>	(927)	
						(421)	X-ray
955	(8 <i>E</i>)-4 α -Acetoxy-12 α ,13 α -epoxycembra-1(15),8-diene	$\text{C}_{22}\text{H}_{34}\text{O}_4$			<i>Chandonanthus hirtellus</i>	(423)	
956	Heteroscyphone A	$\text{C}_{22}\text{H}_{32}\text{O}_7$	217-220	+24.0	<i>Heteroscyphus planus</i>	(421)	X-ray
957	Heteroscyphone B	$\text{C}_{22}\text{H}_{32}\text{O}_6$	211-214	+17.1	<i>Heteroscyphus planus</i>	(423)	
958	Heteroscyphone C	$\text{C}_{22}\text{H}_{32}\text{O}_5$	72-74	-21.4	<i>Heteroscyphus planus</i>	(310)	
959	Heteroscyphone D	$\text{C}_{22}\text{H}_{30}\text{O}_6$	138-140	-13.8	<i>Heteroscyphus planus</i>	(310)	
960	Heteroscyphol	$\text{C}_{20}\text{H}_{32}\text{O}$		-37.5	<i>Heteroscyphus planus</i>	(310)	

961	Heteroscyphic acid A	$C_{20}H_{30}O_2$	-13.5	<i>Heteroscyphus planus</i>	(561)	Cell culture
962	Heteroscyphic acid B	$C_{22}H_{32}O_4$	+2.7	<i>Heteroscyphus planus</i>	(561)	Cell culture
963	Heteroscyphic acid C	$C_{22}H_{32}O_5$	+0.9	<i>Heteroscyphus planus</i>	(561)	Cell culture
964	18-Hydroxy-5,10- <i>trans</i> -cleroda-3,13-(<i>E</i>)-dien-15-oic acid methyl ester	$C_{21}H_{32}O_2$	-25.6	<i>Heteroscyphus planus</i>	(563)	Cell culture
965	Heteroscypholide A (3,4-Epoxy-6,13-diacetoxy-5,10- <i>trans</i> -clerod-14-en-20,12-olide)	$C_{24}H_{34}O_7$	+24.0	<i>Heteroscyphus planus</i>	(563)	Cell culture X-ray
966	Heteroscypholide B (3,4-Epoxy-6-acetoxy-13-hydroxy-5,10- <i>trans</i> -clerod-14-en-20,12-olide)	$C_{22}H_{32}O_6$	+29.4	<i>Heteroscyphus planus</i>	(563)	Cell culture X-ray
967	Kolavelool	$C_{20}H_{34}O$		<i>Pallavicinia subciliata</i>	(702)	
	(-)-Kolavelool	$C_{20}H_{34}O$		<i>Pleurozia gigantea</i>	(490)	
				<i>Jungermannia infusca</i>	(584)	
					(587)	
				<i>Nardia subclavata</i>	(598)	
					(84)	
				<i>Pallavicinia subciliata</i>	(954)	
				<i>Jungermannia infusca</i>	(600)	
968	(+)-Kolavelool (=ent-(13S)-Hydroxy-3,14-clerodadiene)	$C_{20}H_{34}O$	+59.1	<i>Adelanthus lindenbergianus</i>	(116)	
969	13-Hydroxy- <i>cis</i> -ent-cleroda-3,14-diene (<i>cis</i> -ent-Kolavelool)	$C_{20}H_{34}O$	-5.2 -24.2	<i>Jungermannia infusca</i>	(600)	
970	Kolavenol	$C_{20}H_{34}O$		<i>Jungermannia hyalina</i>	(580)	
971	15-Hydroxy- <i>cis</i> -ent-cleroda-3,13(<i>E</i>)-diene	$C_{20}H_{34}O$	-11.1	<i>Pallavicinia subciliata</i>	(702)	
972	15-Hydroxycleroda-3,(13 <i>E</i>)-dien-20-oic acid	$C_{20}H_{32}O_3$		<i>Adelanthus lindenbergianus</i>	(116)	
973	Anastreptin	$C_{20}H_{24}O_5$		<i>Heteroscyphus codlitus</i>	(617)	
				<i>Adelanthus lindenbergianus</i>	(116)	

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ °cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
974	Orcadensin	C ₂₀ H ₂₄ O ₅			<i>Adelanthus lindenbergianus</i>	(116)	
975	1β,12:15,16-Diepoxycis-ent-cleroda-13(16),14-dien-18α,6α-olide	C ₂₀ H ₂₆ O ₄		-69.0	<i>Adelanthus lindenbergianus</i>	(116)	
976	Gymnocolin	C ₂₂ H ₂₆ O ₄			<i>Gymnocolea inflata</i>	(882)	
977	1β,16:15,16-Diepoxycis-ent-cleroda-12,14-dien-18α,6α-olide	C ₂₀ H ₂₆ O ₄		-13.2	<i>Adelanthus lindenbergianus</i>	(116)	
978	8β,12:15,16-Diepoxycis-ent-cleroda-13(16),14-dien-18α,6α-olide	C ₂₀ H ₂₆ O ₄		-33.8	<i>Adelanthus lindenbergianus</i>	(116)	
979	7β,12:8β,12-Diepoxycis-ent-cleroda-13-en-16,15:18α,6α-diolide	C ₂₀ H ₂₄ O ₇		+10.1	<i>Adelanthus lindenbergianus</i>	(116)	
980	1α-Acetoxycis-ent-cleroda-13-en-16,15:18α,6α-diolide	C ₂₂ H ₂₈ O ₈		-14.4	<i>Adelanthus lindenbergianus</i>	(116)	
981	1β,12-Epoxycis-ent-cleroda-13-en-16,15:18α,6α-diolide	C ₂₀ H ₂₆ O ₆		-21.1	<i>Adelanthus lindenbergianus</i>	(116)	
982	7β,12:8β,12-Diepoxycis-ent-cleroda-13-en-15,16:18α,6α-diolide	C ₂₀ H ₂₄ O ₇		+2.1	<i>Adelanthus lindenbergianus</i>	(116)	
982a	7β,12:8β,12-Diepoxycis-ent-cleroda-13-en-15,16:18α,6α-diolide						
983	8β,12-Epoxycis-ent-cleroda-13-en-16,15:18α,6α-diolide	C ₂₀ H ₂₆ O ₆		-4.4	<i>Adelanthus lindenbergianus</i>	(116)	

983a	8 β ,12-Epoxy-15 β -hydroxy- <i>trans</i> -cleroda-13-en-16,15:18 α ,6 α -diolide				
984	8 β ,12-Epoxy-16 α -hydroxy- <i>trans</i> -cleroda-13-en-16,15:18 α ,6 α -diolide and	C ₂₀ H ₂₆ O ₆	−12.0	<i>Adelanthus lindenbergianus</i>	(116)
984a	8 β ,12-Epoxy-16 β -hydroxy- <i>trans</i> -cleroda-13-en-16,15:18 α ,6 α -diolide				
985	3 β ,4 β :15,16-Diepoxy-13 (16),14-clerodadiene	C ₂₀ H ₃₀ O ₂	+32	<i>Thysananthus spathulistipus</i>	(294)
986	Thysaspathone	C ₂₀ H ₂₈ O ₃	−36.3	<i>Thysananthus spathulistipus</i>	(294)
987	<i>ent</i> -3 β ,4 β -Epoxycyclo-(13 <i>E</i>)-en-15-ol	C ₂₀ H ₃₄ O ₂	−31.4	<i>Jungermannia hyalina</i>	(580)
988	(3 <i>R</i> *,4 <i>R</i> *)-Dihydroxycyclo-(13 <i>E</i>)-en-15-al	C ₂₀ H ₃₄ O ₃	−38.4	<i>Jungermannia hyalina</i>	(580)
989	(3 <i>R</i> *,4 <i>R</i> *)-Dihydroxycyclo-(13 <i>Z</i>)-en-15-al	C ₂₀ H ₃₄ O ₃	−45.0	<i>Jungermannia hyalina</i>	(580)
990	<i>ent</i> -3 β ,4 β -Epoxycyclo-(13 <i>Z</i>)-en-15-al	C ₂₀ H ₃₂ O ₂		<i>Jungermannia hyalina</i>	(580)
991	<i>ent</i> -3 β ,4 β -Epoxycyclo-(13 <i>E</i>)-en-15-al	C ₂₀ H ₃₂ O ₂		<i>Jungermannia hyalina</i>	(580)
992	Schistoichilic acid A	C ₂₁ H ₃₂ O ₄		<i>Schistoichila nobilis</i>	(635)
993	Schistoichilic acid B	C ₂₁ H ₃₄ O ₄		<i>Schistoichila nobilis</i>	(635)
994	Dehydrochistoichilic acid B	C ₂₁ H ₃₂ O ₄		<i>Schistoichila nobilis</i>	(635)
995	Schistoichilic acid C	C ₂₁ H ₃₂ O ₅		<i>Schistoichila nobilis</i>	(635)
996	Strictic acid	C ₂₀ H ₂₈ O ₃		<i>Scapania nemorea</i>	(253)
997	<i>seco</i> -Nidoresedic acid methyl ester	C ₂₁ H ₂₈ O ₄	+200.9	<i>Scapania nemorea</i>	(569)
998	Parvixin A	C ₂₂ H ₂₈ O ₆	+61.5	<i>Scapania parvixeta</i>	(393)

Axenic
cultureCell culture
(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ / cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
999	Parvitexin B	C ₂₂ H ₂₈ O ₅		+28.9	<i>Scapania parvitexta</i>	(393)	Cell culture
1000	Parvitexin C	C ₂₀ H ₂₆ O ₄	158-161	+29.2	<i>Scapania parvitexta</i>	(393)	Cell culture
1001	Parvitexin D	C ₂₄ H ₃₂ O ₇		+4.92	<i>Scapania parvitexta</i>	(393)	Cell culture
1002	Parvitexin E	C ₂₂ H ₃₀ O ₆		-7.25	<i>Scapania parvitexta</i>	(393)	Cell culture
1003	Jamesoniellide A	C ₂₁ H ₂₈ O ₆			<i>Jamesoniella autumnalis</i>	(809)	Axenic culture
1004	Jamesoniellide B	C ₂₂ H ₃₀ O ₇			<i>Jamesoniella autumnalis</i>	(809)	Axenic culture
1005	Jamesoniellide C	C ₂₀ H ₂₂ O ₇	199-201	-54.1	<i>Jamesoniella autumnalis</i>	(808) (809)	X-ray Axenic culture
1006	Jamesoniellide D	C ₂₀ H ₂₂ O ₅		-47.9	<i>Jamesoniella autumnalis</i>	(809)	Axenic culture
1007	Jamesoniellide E	C ₂₀ H ₂₂ O ₆		-77.9	<i>Jamesoniella autumnalis</i>	(809)	Axenic culture
1008	Jamesoniellide F	C ₂₀ H ₂₀ O ₆		+32.8	<i>Jamesoniella autumnalis</i>	(809)	Axenic culture
1009	Jamesoniellide G	C ₂₀ H ₂₂ O ₆		-78.4	<i>Jamesoniella autumnalis</i>	(809)	Axenic culture
1010	Jamesoniellide H	C ₂₀ H ₂₄ O ₆		+54.3	<i>Jamesoniella autumnalis</i>	(817)	Axenic culture
1011	Jamesoniellide I	C ₂₁ H ₂₈ O ₆		-1.1	<i>Jamesoniella autumnalis</i>	(817)	Axenic culture
1012	Jamesoniellide J	C ₂₀ H ₂₂ O ₆		-5.9	<i>Jamesoniella autumnalis</i>	(817)	Axenic culture
1013	Jamesoniellide K	C ₂₀ H ₂₂ O ₈		-15.4	<i>Jamesoniella colorata</i>	(340)	Axenic culture
1014	Jamesoniellide L	C ₂₀ H ₂₂ O ₈		-11.8	<i>Jamesoniella colorata</i>	(340)	Axenic culture
1014ab	Jamesoniellide mixture I	C ₂₀ H ₂₂ O ₇		+5.4	<i>Jamesoniella autumnalis</i>	(809)	Axenic culture

1014cd	Jamesoniellide mixture II	C ₂₀ H ₂₂ O ₇	+64.9	<i>Jamesoniella autumnalis</i>	(809)	Axenic culture
1014ef	Jamesoniellide mixture III	C ₂₀ H ₂₂ O ₇	−6.69	<i>Jamesoniella autumnalis</i>	(809)	Axenic culture
1015	1β-Acetoxy-12-hydroxy-15,16-epoxy- <i>cis</i> -cleroda-3,13(16),14-trien-18,6-olide	C ₂₂ H ₂₈ O ₆	−23.2	<i>Jamesoniella autumnalis</i>	(809)	Axenic culture
1016	1β-Acetoxy-7,12-dihydroxy-15,16-epoxy- <i>cis</i> -cleroda-3,13(16),14-trien-18,6-olide	C ₂₂ H ₂₈ O ₇	−13.2	<i>Jamesoniella autumnalis</i>	(815)	Axenic culture
1017	1β-Acetoxy-15,16-epoxy-12,17-dihydroxy- <i>cis</i> -cleroda-3,13(16),14-trien-18,6-olide	C ₂₂ H ₂₈ O ₇		<i>Jamesoniella autumnalis</i>	(809)	Axenic culture
1018	12-Acetoxy-15,16-epoxy-17-hydroxy-methyl- <i>cis</i> -cleroda-3,13(16),14-trien-18,6-olide	C ₂₂ H ₂₈ O ₆	−22.8	<i>Jamesoniella autumnalis</i>	(815)	Axenic culture
1019	8-Hydroxy-15,16-epoxy- <i>cis</i> -cleroda-3,13(16),14-triene-18,6:20,12-diolide	C ₂₀ H ₂₂ O ₆	−66.7	<i>Jamesoniella autumnalis</i>	(815)	Axenic culture
1020	15,16-Epoxy-1,3,13(16),14-clerodatetraene-17,12:18,6-diolide	C ₂₂ H ₂₀ O ₅	253-255	<i>Jamesoniella autumnalis</i>	(815)	Axenic culture
1021	15,16-Epoxy-8-hydroxy-1,3,13(16),14-clerodatetraene-17,12:18,6-diolide	C ₂₀ H ₂₀ O ₆	−38.9	<i>Jamesoniella autumnalis</i>	(810)	Axenic culture
1022	15-Carboxy-8β,16-dihydroxy-1,3,13 <i>E</i> -clerodatriene-17,12:18,6-diolide	C ₂₂ H ₂₂ O ₈	−218.7	<i>Jamesoniella autumnalis</i>	(815)	Axenic culture
1023	15-Carboxy-8β,16-dihydroxy-1,3,13 <i>Z</i> -clerodatriene-17,12:18,6-diolide	C ₂₂ H ₂₂ O ₈	−223.9	<i>Jamesoniella autumnalis</i>	(815)	Axenic culture
1024	<i>ent</i> -Cleroda-3,13(16),14-triene	C ₂₀ H ₃₂	−33.9	<i>Jungermannia infusca</i>	(592) (597)	Axenic culture

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ /° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1025	Cleroda-3,13(16),14-trien-17-ol	C ₂₀ H ₃₂ O		-45.0	<i>Jungermannia infusca</i>	(592)	
1026	Cleroda-3,13(16),14-trien-17-al	C ₂₀ H ₃₀ O			<i>Jungermannia infusca</i>	(597)	
1027	Infuscaic acid (Cleroda-3,13(16),14-trien-17-oic acid)	C ₂₀ H ₃₀ O ₂			<i>Jungermannia infusca</i>	(592)	
1028	bis- <i>nor</i> -Infuscaic acid	C ₁₈ H ₂₈ O ₃		-40.5	<i>Jungermannia infusca</i>	(597)	
1029	2β-Acetoxy-18-carboxymethylcleroda-3,13-dien-15-oic acid	C ₂₃ H ₃₄ O ₆		+32.8	<i>Scapania bolanderi</i>	(592)	
1030	<i>ent</i> -6β-Hydroxycleroda-3, (12 <i>E</i>), 14-triene	C ₂₀ H ₃₄ O		-40.9	<i>Heteroscyphus billardieri</i>	(607)	
1031	<i>ent</i> -2β-Hydroxycleroda-3, (12 <i>E</i>), 14-triene	C ₂₀ H ₃₄ O			<i>Heteroscyphus billardieri</i>	(635)	
1032	4,13-Dihydroxycleroda-14-ene	C ₂₀ H ₃₆ O ₂			<i>Heteroscyphus billardieri</i>	(635)	
1033	Bacchasalicylic acid	C ₂₀ H ₃₂ O ₃		-70.5	<i>Jungermannia infusca</i>	(592)	X-ray
1034	<i>ent</i> -Cleroda-3, (13 <i>E</i>)-dien-15-al-17-oic acid (= (13 <i>E</i>)-Symphyoretic acid)	C ₂₀ H ₃₀ O ₃			<i>Jungermannia infusca</i>	(592)	
1035	<i>ent</i> -Cleroda-3, (13 <i>E</i>)-diene-15,17-dial	C ₂₀ H ₃₀ O ₂			<i>Jungermannia infusca</i>	(597)	
1036	17-Hydroxycleroda-3, (13 <i>E</i>)-dien-15-al	C ₂₀ H ₃₂ O ₂		-94.5	<i>Jungermannia infusca</i>	(597)	
1037	15-Hydroxycleroda-3, (13 <i>E</i>)-dien-17-al	C ₂₀ H ₃₂ O ₂			<i>Jungermannia infusca</i>	(597)	
1038	<i>ent</i> -Cleroda-3, (13 <i>Z</i>)-dien-15-al-17-oic acid (= (13 <i>Z</i>)-Symphyoretic acid)	C ₂₀ H ₃₀ O ₃			<i>Jungermannia infusca</i>	(592)	
1039	<i>ent</i> -Cleroda-3, (13 <i>Z</i>)-diene-15,17-dial	C ₂₀ H ₃₀ O ₂			<i>Jungermannia infusca</i>	(592)	

1040	17-Hydroxycleroda-3,(13 <i>Z</i>)-dien-15-al	C ₂₀ H ₃₂ O ₂	-152.9	<i>Jungermannia infusca</i>	(597)	
1041	Infuscolide A	C ₂₀ H ₂₆ O ₃	-90.9	<i>Jungermannia infusca</i>	(597)	X-ray
1042	(-)- <i>epi</i> -Hardwickiic acid	C ₂₀ H ₂₈ O ₃	130-132	<i>Scapania nemorea</i>	(253)	Axenic culture
1043	(-)- <i>cis</i> -Cleroda-3,13-dien-16-hydroxy-18-oic acid-15,16-olide	C ₂₀ H ₂₆ O ₃	-190.6	<i>Scapania nemorea</i>	(253)	Axenic culture
1044	5- <i>epi</i> -Nidoresedic acid	C ₂₀ H ₂₆ O ₃	-425.0	<i>Scapania nemorea</i>	(253)	Axenic culture
1045	(-)- <i>cis</i> -Cleroda-1,3,13-trien-18-oic acid-15,16-olide	C ₂₀ H ₂₆ O ₄	-203.8	<i>Scapania nemorea</i>	(253)	Axenic culture
1046	(-)- <i>cis</i> -Cleroda-1,3,13-trien-16-hydroxy-18-oic acid-15,16-olide	C ₂₀ H ₂₆ O ₅	-161.7	<i>Scapania nemorea</i>	(253)	Axenic culture
1047	(-)- <i>cis</i> -Cleroda-1,3,13-trien-15-hydroxy-18-oic acid-16,15-olide	C ₂₀ H ₂₆ O ₅	-201.8	<i>Scapania nemorea</i>	(253)	Axenic culture
1048	(-)-15,16-Epoxy- <i>cis</i> -cleroda-3,13(16),14-trien-18,6 <i>α</i> -diolide	C ₂₀ H ₂₆ O ₃		<i>Scapania nemorea</i>	(253)	Axenic culture
1049	(-)-15,16-Epoxy- <i>cis</i> -cleroda-3,13(16),14-trien-12-hydroxy-18,6 <i>α</i> -olide	C ₂₀ H ₂₆ O ₄	-10.4	<i>Scapania nemorea</i>	(253)	Axenic culture
1050	(-)- <i>cis</i> -Cleroda-3,13-dien-12,16-dihydroxy-15,16:18,6 <i>α</i> -diolide	C ₂₀ H ₂₆ O ₆	-221.1	<i>Scapania nemorea</i>	(253)	Axenic culture
1051	(-)- <i>cis</i> -Cleroda-3,13-dien-12,15-dihydroxy-17-oic acid-16,15:18,6 <i>α</i> -diolide	C ₂₀ H ₂₄ O ₃	-199.7	<i>Scapania nemorea</i>	(253)	Axenic culture
1052	Coloratanolide	C ₂₁ H ₂₄ O ₆	-1.2	<i>Jamesoniella colorata</i>	(635) (899) (901)	

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1053	15,16-Epoxy- <i>cis</i> -cleroda-3,13 (16),14-trien-18-oic acid	C ₂₀ H ₂₈ O ₃			<i>Diplophyllum plicatum</i>	(84)	
1054	15,16-Epoxy- <i>cis</i> -cleroda-13 (16),14-dien-18 α ,6 α -olide	C ₂₀ H ₂₈ O ₃			<i>Diplophyllum plicatum</i>	(84)	
1055	2 β ,9 α -Dihydroxyverrucosane	C ₂₀ H ₃₄ O ₂			<i>Fossombronina angulosa</i>	(492)	
1056	13- <i>epi</i> -Neoverrucosan-5 β -ol	C ₂₀ H ₃₄ O	147	+42.1	<i>Dendromastigophora flagellifera</i>	(635)	
					<i>Fossombronina alaskana</i>	(269)	Axenic culture
					<i>Heteroscyphus planus</i>	(310)	
					<i>Jamesoniella tasmanica</i>	(72)	
						(872)	
					<i>Lepicolea ochroleuca</i>	(478)	
					<i>Plagiochila circinalis</i>	(635)	
						(897)	
					<i>Plagiochila dusenii</i>	(32)	
					<i>Plagiochila validissima</i>	(32)	
					<i>Schistochila nobilis</i>	(635)	
1057	13- <i>epi</i> -Neoverrucosan-5 β ,20-diol	C ₂₀ H ₃₄ O ₂	157-159	+56.3	<i>Heteroscyphus planus</i>	(310)	
					<i>Plagiochila circinalis</i>	(635)	
1058	13- <i>epi</i> -Neoverrucosan-5 β ,6 α -diol	C ₂₀ H ₃₄ O ₂		+63	<i>Plagiochila validissima</i>	(32)	
1059	13- <i>epi</i> -Neoverrucosan-5 β ,12 β -diol	C ₂₀ H ₃₄ O ₂			<i>Plagiochila dusenii</i>	(32)	
1060	6 α -Acetoxy-13- <i>epi</i> -neoverrucosan-5 β ,12 β -diol	C ₂₂ H ₃₆ O ₄		+59	<i>Plagiochila dusenii</i>	(32)	
1061	8 α -Acetoxy-13- <i>epi</i> -neoverrucosan-5 β ,12 β -diol	C ₂₂ H ₃₆ O ₄		+72	<i>Plagiochila dusenii</i>	(32)	
1062	5-Oxo- <i>epi</i> -neoverrucosan	C ₂₀ H ₃₂ O	92	+177.2	<i>Fossombronina alaskana</i>	(269)	Axenic culture X-ray

1063	8 α ,16-Diacetoxy-13-hydroxy-5-oxo- <i>epi</i> -neoverrucosane	C ₂₄ H ₃₆ O ₆	125	+118.1	<i>Fossombronina alaskana</i>	(269)	Axenic culture
1064	20-Acetoxy-13- <i>epi</i> -neoverrucosan-5 β ,12 β -diol	C ₂₂ H ₃₆ O ₄		+42.2	<i>Jamesoniella tasmanica</i>	(72) (872)	Axenic culture
1065	13-Hydroxy-5-oxo- <i>epi</i> -neoverrucosane	C ₂₀ H ₃₂ O ₂	104	+123.4	<i>Fossombronina alaskana</i>	(269)	Axenic culture
1066	8 α -Acetoxy-13-hydroxy-5-oxo- <i>epi</i> -neoverrucosane	C ₂₂ H ₃₄ O ₄	165	+71.3	<i>Fossombronina alaskana</i>	(269)	Axenic culture
1067	8 α ,13-Dihydroxy-5-oxo- <i>epi</i> -neoverrucosane	C ₂₀ H ₃₂ O ₃	115	+108.1	<i>Fossombronina alaskana</i>	(269)	Axenic culture
1068	20-Acetoxy-4 β ,5 β -epoxy-13- <i>epi</i> -neohomoverrucos-15(17)-en-16,12 β -olide	C ₂₂ H ₃₀ O ₅		+24.6	<i>Jamesoniella tasmanica</i>	(72) (872)	
1069	20-Acetoxy-4 β ,5 β -epoxy-13 α -hydroxy-13- <i>epi</i> -neohomoverrucos-15(17)-en-16,12 β -olide	C ₂₂ H ₃₀ O ₆	190-192	+43.2	<i>Jamesoniella tasmanica</i>	(72) (872)	
1070	20-Acetoxy-4 β ,5 β -epoxy-14 α -hydroxy-13- <i>epi</i> -neohomoverrucos-15(17)-en-16,12 β -olide	C ₂₂ H ₃₀ O ₆	219-220	+18.7	<i>Jamesoniella tasmanica</i>	(72) (872)	
1071	5,18-Dihydroxy- <i>epi</i> -homoverrucosane	C ₂₀ H ₃₄ O ₂			<i>Fossombronina alaskana</i>	(269)	Axenic culture
1072	13- <i>epi</i> -Homoverrucosan-5 β ,20-diol	C ₂₀ H ₃₄ O ₂		+37	<i>Fossombronina angulosa</i> <i>Plagiochila dusenii</i>	(492) (32)	
1073	13- <i>epi</i> -Homoverrucosan-5 β -ol	C ₂₀ H ₃₄ O			<i>Plagiochila circinalis</i>	(635)	
1074	13- <i>epi</i> -Homoverrucosan-5 β ,6 β -diol	C ₂₀ H ₃₄ O ₂		+20.3	<i>Plagiochila cristata</i> <i>Plagiochila cristata</i>	(910) (910)	
1075	13- <i>epi</i> -Homoverrucosan-5 β ,6 β ,8 β -triol	C ₂₀ H ₃₄ O ₃	251-254	-19.5	<i>Plagiochila cristata</i>	(910)	X-ray
1076	13- <i>epi</i> -Homoverrucosan-5 β ,6 β -diol-8-one	C ₂₀ H ₃₂ O ₃		-28.0	<i>Plagiochila cristata</i>	(910)	

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1077	13- <i>epi</i> -Homoverrucosan-6 β -ol-5-one	C ₂₀ H ₃₂ O ₂		-37.7	<i>Plagiochila cristata</i>	(910)	
1078	18-Hydroxydolabell-(7 <i>E</i>)-en-3-one	C ₂₀ H ₃₄ O ₂			<i>Barbilophozia barbata</i> <i>Barbilophozia floerkei</i> <i>Barbilophozia lycopodioides</i> <i>Barbilophozia barbata</i>	(583) (583) (583) (583) (596)	
1079	10-Deacetoxybarbilycopodin	C ₂₂ H ₃₆ O ₄			<i>Chandonanthus hirtellus</i>	(927)	
1080	Dolabella-(3 <i>E</i>), (7 <i>E</i>), 18-trien-2 α -ol	C ₂₀ H ₃₂ O		-3			
1081	2 α , 10 α -Diacetoxy-7, 8, 18, 19-diepoxydolabell-(3 <i>E</i>)-en-14-one	C ₂₄ H ₃₄ O ₇	163-165	+55	<i>Chandonanthus hirtellus</i>	(927)	X-ray
1082	2 α , 10 α , 14 α -Triacetoxy-7, 8, 18, 19-diepoxydolabell-(3 <i>E</i>)-ene	C ₂₆ H ₃₉ O ₈		+1	<i>Chandonanthus hirtellus</i>	(927)	
1083	10 α , 14 α -Diacetoxy-7, 8-epoxydolabell-(3 <i>E</i>), 18-dien-2 α -ol	C ₂₂ H ₃₂ O ₄		+17	<i>Chandonanthus hirtellus</i>	(927)	
1084	2 α , 10 α -Diacetoxy-7, 8-epoxydolabell-(3 <i>E</i>), 18-ene	C ₂₄ H ₃₆ O ₅		+25	<i>Chandonanthus hirtellus</i>	(927)	
1085	Acetoxyodontoschismenol	C ₂₂ H ₃₆ O ₃			<i>Odontoschisma denudatum</i>	(316)	
1086	Acetoxyodontoschismenetriol	C ₂₂ H ₃₆ O ₅	208-210	+33.3	<i>Odontoschisma denudatum</i>	(317)	
1087	6 β -Acetoxy-10 β , 12 β -dihydroxydolabell-(3 <i>E</i> , 7 <i>E</i>)-dien-16-al	C ₂₂ H ₃₄ O ₅			<i>Odontoschisma denudatum</i>	(316)	
1088	6 β -Acetoxy-10 β , 12 β -dihydroxydolabell-(3 <i>Z</i> , 7 <i>E</i>)-dien-16-al	C ₂₂ H ₃₄ O ₅			<i>Odontoschisma denudatum</i>	(316)	
1089	6 β -Acetoxy-10 β , 12 β -dihydroxydolabell-(3 <i>E</i> , 7 <i>E</i>)-dien-16-oic acid	C ₂₂ H ₃₄ O ₆			<i>Odontoschisma denudatum</i>	(316)	

1090	Denudatenal A			+58.8		<i>Odontoschisma denudatum</i>	(326)
1091	Denudatenal B			+58.8		<i>Odontoschisma denudatum</i>	(326)
1092	Denudatenal C			-65.2	85-86	<i>Odontoschisma denudatum</i>	(326)
1093	Denudatenal D			-36.2		<i>Odontoschisma denudatum</i>	(326)
1094	12 β -Hydroxydoladella-(3 <i>E</i> ,7 <i>E</i>)-diene					<i>Plagiochila sciophila</i>	(326)
1095	2,5-Fusicoccadiene					<i>Anastrophyllum auritum</i>	(976)
						<i>Bazzania involuta</i>	(72)
						<i>Chandonanthus hirtellus</i>	(494)
						<i>Frullania falciloba</i>	(423)
						<i>Frullania incumbens</i>	(78)
						<i>Frullania media</i>	(72)
						<i>Frullania monocera</i>	(78)
						<i>Frullania patula</i>	(78)
						<i>Frullania pycnantha</i>	(78)
						<i>Frullania squarrosula</i>	(78)
						<i>Lepidozia concinna</i>	(78)
						Unidentified <i>Frullania</i> sp.	(72)
						<i>Lophozia ventricosa</i>	(424)
						<i>Plagiochila aerea</i>	(486)
						<i>Plagiochila buchtiniana</i>	(334)
						<i>Plagiochila circinalis</i>	(330)
						<i>Plagiochila diversifolia</i>	(72)
						<i>Plagiochila dusenii</i>	(330)
						<i>Plagiochila porelloides</i>	(32)
						<i>Plagiochila retrorsa</i>	(762)
						<i>Plagiochila rutilans</i>	(698)
						<i>Plagiochila stricta</i>	(693)
						<i>Plagiochila yokogurensis</i>	(699)

(continued)

Number	Compound	Formula	Yield (%)	Plant	Method	Notes
1100	3 α -Hydroxyfusiococca-2(6)-en-5-one	C ₂₀ H ₃₂ O ₂	+9.4	<i>Plagiochila cristata</i> <i>Plagiochila dusenii</i> <i>Plagiochila validissima</i> <i>Plagiochila yokogurensis</i> <i>Plagiochila spinulosa</i>	(910) (32) (32) (84) (617)	Axenic culture
1101	Fusicoincurvatonone A	C ₂₀ H ₃₂ O ₂		<i>Plagiochila dusenii</i>	(32)	
1102	Fusicogigantepoxide	C ₂₀ H ₃₂ O ₂		<i>Bryopteris filicina</i> <i>Chandonanthus hirtellus</i>	(576) (421) (423) (494)	X-ray
				<i>Frullania falcitoba</i> <i>Frullania monocera</i> <i>Frullania patula</i> <i>Frullania pycnantha</i> <i>Frullania squarrosula</i>	(78) (78) (78) (78) (78)	
1103	Barbifusiococcin A	C ₂₀ H ₃₄ O ₂		<i>Plagiochila dusenii</i> <i>Barbilophozia barbata</i> <i>Barbilophozia lycopodioides</i> <i>Barbilophozia barbata</i> <i>Bryopteris filicina</i> <i>Chandonanthus hirtellus</i>	(32) (596) (583) (596) (604) (421) (423)	
1104	Barbifusiococcin B	C ₂₀ H ₃₄ O ₂		<i>Lepicolea ochroleuca</i>	(478)	
1105	Anadensin	C ₂₀ H ₃₂ O ₂		<i>Plagiochila asplenioides</i> <i>Plagiochila circinalis</i>	(441) (635) (897)	
				<i>Plagiochila dusenii</i> <i>Plagiochila spinulosa</i> <i>Plagiochila corrugata</i> <i>Anastrophyllum auritum</i>	(32) (617) (842) (976)	X-ray
1106	Fusicorrugatol	C ₂₄ H ₃₈ O ₇	-10.9			
1107	Fusicoauritone	C ₂₀ H ₃₂ O ₂	+14.0			

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ / ° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
					<i>Chandonanthus hirtellus</i>	(422)	
					<i>Lepicolea ochroleuca</i>	(423)	
					<i>Plagiochila circinalis</i>	(478)	
						(635)	
						(897)	
					<i>Plagiochila dusenii</i>	(32)	
					<i>Chandonanthus hirtellus</i>	(422)	
						(423)	
					<i>Chandonanthus hirtellus</i>	(422)	
						(423)	
					<i>Plagiochila sciophila</i>	(326)	
					<i>Plagiochila sciophila</i>	(326)	
					<i>Plagiochila ovalifolia</i>	(701)	
					<i>Plagiochila ovalifolia</i>	(701)	
					<i>Plagiochila ovalifolia</i>	(701)	
					<i>Plagiochila ovalifolia</i>	(701)	
					<i>Plagiochila ovalifolia</i>	(701)	
					<i>Plagiochila ovalifolia</i>	(701)	
					<i>Plagiochila ovalifolia</i>	(701)	
					<i>Plagiochila circinalis</i>	(635)	
						(897)	
					<i>Plagiochila circinalis</i>	(635)	
						(897)	
					<i>Plagiochila circinalis</i>	(635)	
						(897)	
					<i>Plagiochila yokogurensis</i>	(84)	
1108	Fusicoauritone 6 α -methyl ether	C ₂₁ H ₃₄ O ₂					
1109	6 β ,10 β -Epoxy-5 β -hydroxy-fusicocc-2-ene	C ₂₀ H ₃₂ O ₂		+73			
1110	14 β -Hydroxyfusicocc-3(16)-ene	C ₂₀ H ₃₄ O					
1111	7 α ,14 β -Dihydroxyfusicocc-3(16)-ene	C ₂₀ H ₃₄ O ₂					
1112	Fusicoplugin A	C ₂₄ H ₃₈ O ₇					
1113	Fusicoplugin B	C ₂₆ H ₄₀ O ₈					
1114	Fusicoplugin C	C ₂₄ H ₃₆ O ₇					
1115	Fusicoplugin E	C ₂₀ H ₃₂ O		-17.0			
1116	Fusicoplugin F	C ₂₀ H ₃₄ O ₂		-1.3			
1117	Fusicoplugin G	C ₂₄ H ₃₈ O ₇		-51.5			
1118	Fusicoplugin H	C ₂₆ H ₄₀ O ₈		-12.3			
1119	Fusicoplugin I	C ₂₂ H ₃₆ O ₅		-21.7			
1120	Fusicoccane-labdane dimer 1	C ₄₂ H ₆₈ O ₃		+41.6			
1121	Fusicoccane-labdane dimer 2	C ₄₂ H ₆₈ O ₃		-33.1			
1122	Fusicoccane-labdane dimer 3	C ₄₂ H ₆₈ O ₄		-68.5			
1123	Fusicoccane-aromadendrane dimer	C ₃₄ H ₅₂ O ₃					

1124	Spinuloplagin A	$C_{37}H_{48}O_5$		<i>Plagiochila spinulosa</i>	(617)	
1125	Spinuloplagin B	$C_{37}H_{48}O_5$		<i>Plagiochila spinulosa</i>	(617)	
1126	3 ξ -Hydroxy-5(10),(13E)-halimadien-15-al	$C_{20}H_{32}O_2$	+104.8	<i>Jungermannia hyalina</i>	(580)	
1127	5(10),14-Halimadien-13-ol	$C_{20}H_{34}O$	-124.1	<i>Jungermannia infusca</i>	(600)	
1128	1(10),14-Halimadien-13 ξ -ol	$C_{20}H_{34}O$	-60.2	<i>Jungermannia infusca</i>	(598)	
1129	1(10),14-Halimadien-13 ξ -ol	$C_{20}H_{34}O$	+28.2	<i>Plagiochila barteri</i>	(295)	
1130	Halimane-type dilactone	$C_{22}H_{30}O_6$	+19.7	<i>Heteroscyphus coalitus</i>	(873)	
1131	3,4- <i>sec</i> -Halimane-type dilactone	$C_{21}H_{28}O_6$	+43.3	<i>Heteroscyphus coalitus</i>	(873)	
1132	Isophyllocadene	$C_{20}H_{32}$		<i>Bazzania japonica</i>	(485)	
1133	<i>ent</i> -16-Kaurene	$C_{20}H_{32}O$		<i>Apometzgeria pubescens</i>	(882)	
				<i>Cuspidatula monodon</i>	(72)	
				<i>Frullania aterrima</i> var. <i>aterrima</i>	(78)	
				<i>Jungermannia subulata</i>	(822)	
				<i>Plagiochila yokogurensis</i>	(84)	
1134	<i>ent</i> -16-Kauren-19-ol	$C_{20}H_{32}O$		<i>Jamesoniella kirkii</i>	(84)	
				<i>Jamesoniella tasmanica</i>	(612)	
				<i>Jamesoniella tasmanica</i>	(72)	
1135	<i>ent</i> -16-Kauren-19-oic acid	$C_{20}H_{30}O_2$		<i>Jamesoniella kirkii</i>	(872)	
				<i>Jamesoniella kirkii</i>	(84)	
1136	Methyl <i>ent</i> -16-kauren-19-oate	$C_{21}H_{32}O_2$		<i>Jamesoniella kirkii</i>	(612)	
1137	<i>ent</i> -16-Kaurene-3 β ,19-diol	$C_{20}H_{32}O_2$		<i>Jamesoniella tasmanica</i>	(84)	
				<i>Jamesoniella tasmanica</i>	(612)	
1138	<i>ent</i> -3 β -Acetoxy-16-kauren-19-ol	$C_{22}H_{34}O_3$	153-154	<i>Jamesoniella tasmanica</i>	(72)	
			-72.0	<i>Jamesoniella tasmanica</i>	(872)	
1139	<i>ent</i> -19-Acetoxy-16-kauren-3 β -ol	$C_{22}H_{34}O_3$	-52.1	<i>Jamesoniella tasmanica</i>	(72)	
				<i>Jamesoniella tasmanica</i>	(872)	
1140	<i>ent</i> -3 β -Hydroxy-16-kaurene	$C_{20}H_{32}O$		<i>Herbertus alpinus</i>	(872)	
					(558)	

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1141	ent-7β-Hydroxy-16-kaurene	C ₂₀ H ₃₂ O			<i>Jungmannia truncata</i>	(136)	
1142	ent-7β-Hydroxy-16-kauren-15-one	C ₂₀ H ₃₀ O ₂	142-144	-112	<i>Jungmannia truncata</i>	(136) (477)	
1143	ent-3α-Hydroxy-16-kauren-15-one	C ₂₀ H ₃₀ O ₂			<i>Lepidolaena taylorii</i> <i>Jungmannia truncata</i>	(654) (136) (477)	
1144	ent-16-Kauren-15-one	C ₂₀ H ₃₀ O			<i>Jackiella javanica</i> <i>Jungmannia exsertifolia</i> subsp. <i>cordifolia</i> <i>Jungmannia infusca</i> <i>Jungmannia subulata</i>	(601) (608) (586) (599) (629) (822)	
					<i>Jungmannia truncata</i>	(136) (477)	
					Unidentified <i>Jungmannia</i> sp.	(601) (609)	
					<i>Lepidolaena taylorii</i> <i>Porella densifolia</i>	(610) (654) (669)	
1145	ent-7β,15β-Dihydroxy-16-kaurene	C ₂₀ H ₃₂ O ₂			<i>Jungmannia truncata</i>	(136)	
1146	ent-7β,15α-Dihydroxy-16-kaurene	C ₂₀ H ₃₂ O ₂			<i>Jungmannia truncata</i> <i>Plagiochila pulcherrima</i>	(136) (477)	
1147	ent-7β,20-Dihydroxy-16-kauren-15-one	C ₂₀ H ₃₂ O ₃			<i>Jungmannia truncata</i>	(136)	
1148	ent-15α-Hydroxy-16-kaurene	C ₂₀ H ₃₂ O			<i>Jackiella javanica</i>	(587)	
					<i>Jungmannia exsertifolia</i> subsp. <i>cordifolia</i>	(608) (586)	
					<i>Jungmannia infusca</i>	(592)	

1149	(16 <i>R</i>)- <i>ent</i> -7 β -Hydroxykauran-15-one	C ₂₀ H ₃₂ O ₂	<i>Jungermannia subulata</i> (599)
1150	(16 <i>S</i>)- <i>ent</i> -7 β -Hydroxykauran-15-one	C ₂₀ H ₃₂ O ₂	<i>Jungermannia truncata</i> (600)
1151	(16 <i>R</i>)- <i>ent</i> -7 β ,20-Dihydroxykauran-15-one	C ₂₀ H ₃₂ O ₃	<i>Plagiochila pulcherrima</i> (822)
1152	(16 <i>S</i>)- <i>ent</i> -7 β ,20-Dihydroxykauran-15-one	C ₂₀ H ₃₂ O ₃	<i>Jungermannia truncata</i> (136)
1153	(16 <i>R</i>)- <i>ent</i> -Kauran-15-one	C ₂₀ H ₃₂ O	<i>Jungermannia truncata</i> (601)
1154	<i>ent</i> -16 β -Hydroxykaurane	C ₂₀ H ₃₄ O	<i>Jungermannia truncata</i> (136)
1155	(16 <i>R</i>)- <i>ent</i> -11 α -Hydroxykauran-15-one	C ₂₀ H ₃₂ O ₂	<i>Jungermannia truncata</i> (601)
1156	Nardiin	C ₂₀ H ₂₈ O ₂	Unidentified <i>Jungermannia</i> sp. (602)
1157	<i>ent</i> -11 α -Hydroxy-16-karene	C ₂₀ H ₃₂ O	<i>Jungermannia exsertifolia</i> (586)
1158	<i>ent</i> -11 α -Hydroxy-16-karene-15-one	C ₂₀ H ₃₀ O ₂	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (601)
			<i>Jungermannia truncata</i> (587)
			<i>Jackiella javanica</i> (608)
			<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (586)
			<i>Jungermannia infusca</i> (599)

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
					<i>Jungermannia truncata</i>	(136) (477)	
					<i>Jungermannia subulata</i>	(601)	
1159	<i>ent</i> -11 α -Hydroxy-16-kauren-15 α -yl acetate	C ₂₂ H ₃₂ O ₃			Unidentified <i>Jungermannia</i> sp.	(629) (602)	
1160	<i>ent</i> -16-Kauren-11 α ,15 α -diol	C ₂₀ H ₃₀ O ₂			<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(586) (586)	
					<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(601)	
					Unidentified <i>Jungermannia</i> sp.	(609) (610)	
1161	<i>ent</i> -6 α -Hydroxy-16-kauren-15-one	C ₂₀ H ₃₀ O ₂			Unidentified <i>Jungermannia</i> sp.	(609)	
1162	<i>ent</i> -11 α -Acetoxy-7 β -hydroxy-16-kauren-5-one	C ₂₂ H ₃₀ O ₄			Unidentified <i>Jungermannia</i> sp.	(609) (610)	
1163	<i>ent</i> -14 α -Hydroxy-16-kauren-15-one	C ₂₀ H ₃₀ O ₂		-98.1	<i>Jungermannia infusca</i> <i>Jungermannia truncata</i>	(599) (477) (601)	
1164	Rostronol F	C ₂₂ H ₃₂ O ₆			<i>Lepidolaena taylorii</i> <i>Jungermannia infusca</i>	(654) (599)	
1165	16,17-Dihydronastronol F	C ₂₂ H ₃₄ O ₆			<i>Jungermannia truncata</i> <i>Jungermannia infusca</i>	(601) (599)	
1166	<i>ent</i> -1 β -Hydroxykauran-12-one	C ₂₀ H ₃₂ O ₂			<i>Jungermannia truncata</i> <i>Paraschistochila pinnatifolia</i>	(601) (84) (483)	
1167	<i>ent</i> -12 β -Hydroxykaurane	C ₂₀ H ₃₄ O ₀			<i>Paraschistochila pinnatifolia</i>	(84)	
1168	Exsertifolin A	C ₄₄ H ₆₂ O ₁₀	198-200	-67.6	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(586)	X-ray

1169	Exsertifolin B	C ₂₂ H ₃₀ O ₅	+62.1	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(586)	
1170	Exsertifolin C	C ₂₂ H ₃₂ O ₅	+97.2	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(586)	X-ray
1171	Exsertifolin D	C ₂₄ H ₃₄ O ₇	+40.3	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(586)	
1172	Exsertifolin E	C ₂₄ H ₃₂ O ₇	+50.1	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(586)	X-ray
1173	Exsertifolin F	C ₂₂ H ₃₀ O ₄	+103.0	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(586)	
1174	Exsertifolin G	C ₂₀ H ₂₈ O ₂	+115.2	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(586)	
1175	Exsertifolin H	C ₂₀ H ₃₀ O ₂	+56.5	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(586)	
1176	Secoexsertifolin A	C ₂₄ H ₃₄ O ₈	−40.7	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(586)	X-ray
1177	Secoexsertifolin B	C ₂₄ H ₃₄ O ₈	−25.8	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i>	(586)	
1178	Rabdoumbrosanin	C ₂₀ H ₂₈ O ₃	−66	<i>Lepidolaena palpebrifolia</i> <i>Lepidolaena taylorii</i>	(654) (652) (654)	
1179	16,17-Dihydorabdoumbrosanin	C ₂₀ H ₃₀ O ₃	−11	<i>Lepidolaena taylorii</i>	(652)	
1180	8,14-Epoxyabdoumbrosanin	C ₂₀ H ₂₈ O ₄	−53	<i>Lepidolaena palpebrifolia</i>	(654)	
1181	<i>ent</i> -8,9- <i>seco</i> -7 β -Acetoxykaur-8 (14),16-dien-9,15-dione	C ₂₂ H ₃₀ O ₄		<i>Lepidolaena taylorii</i>	(652)	
1182	<i>ent</i> -8,9- <i>seco</i> -7 β -Acetoxyl-11 α - hydroxykaur-8(14),16-dien- 9,15-dione	C ₂₂ H ₃₀ O ₅		<i>Lepidolaena taylorii</i>	(654)	

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1183	<i>ent</i> -8,9- <i>seco</i> -7 β -Hydroxy-11 α -acetoxykaur-8(14),16-dien-9,15-dione	C ₂₂ H ₃₀ O ₅			<i>Lepidolaena taylorii</i>	(654)	
1184	<i>ent</i> -8,9- <i>seco</i> -7 β ,11 α -Dihydroxykaur-8(14),16-dien-9,15-dione	C ₂₀ H ₂₈ O ₄			<i>Lepidolaena taylorii</i>	(654)	
1185	<i>ent</i> -7 β ,14 α -Dihydroxykaur-16-en-15-one	C ₂₀ H ₃₀ O ₃			<i>Lepidolaena taylorii</i>	(654)	
1186	<i>ent</i> -7 β -Acetoxy-14 α -hydroxykaur-16-en-15-one	C ₂₂ H ₃₂ O ₄			<i>Lepidolaena taylorii</i>	(654)	
1187	<i>ent</i> -3 β -Acetoxy-7 β ,9 α ,14 α -trihydroxykaur-16-en-15-one (=Shikocidin)	C ₂₂ H ₃₂ O ₆			<i>Lepidolaena taylorii</i>	(654)	
1188	Rotundic acid A (= <i>ent</i> -15 α -Hydroxykaur-16-en-20-oic acid)	C ₂₀ H ₃₀ O ₃	215-217	-15.2	<i>Jungermannia rotundata</i>	(588)	
1189	Rotundic acid B (= <i>ent</i> -15 α -Acetoxykaur-16-en-20-oic acid)	C ₂₃ H ₃₂ O ₄	195-196	-39.7	<i>Jungermannia rotundata</i>	(588)	
1190	Rotundic acid C (= <i>ent</i> -9 α -Hydroxykaur-16-en-20-oic acid)	C ₂₀ H ₃₀ O ₃	255-257	-16.1	<i>Jungermannia rotundata</i>	(588)	
1191	<i>ent</i> -Kaurane-3,15-dione	C ₂₀ H ₃₀ O ₂	176-178	-117.4 -157.2	<i>Jungermannia truncata</i> <i>Jungermannia subulata</i>	(477) (629) (822)	X-ray Cell culture Cell culture
1192	<i>ent</i> -Kaur-16-en-3,15-dione	C ₂₀ H ₂₈ O ₂		-126.6	<i>Jungermannia truncata</i> <i>Jungermannia subulata</i>	(477) (629)	Cell culture X-ray

1193	15 β -Hydroxy- <i>ent</i> -kaur-16-en-3-one	C ₂₀ H ₃₀ O ₂	129-132	-70.9	<i>Jungermannia subulata</i>	(629)	Cell culture, X-ray
1194	13 α -Hydroxy- <i>ent</i> -kauran-3,15-dione	C ₂₀ H ₃₀ O ₃	171-178	-132.3	<i>Jungermannia subulata</i>	(629)	Cell culture
1195	13 α ,15 α -Dihydroxy- <i>ent</i> -kaur-16-en-3-one	C ₂₀ H ₃₀ O ₃	165-171	-27.5	<i>Jungermannia subulata</i>	(629)	Cell culture
1196	7 β -Hydroxy- <i>ent</i> -kaur-16-en-15-one	C ₂₀ H ₃₀ O ₂	125-128	-75.0	<i>Jungermannia subulata</i>	(629)	X-ray
1197	13 α -Acetoxy- <i>ent</i> -kaur-16-en-3,15-dione	C ₂₂ H ₃₀ O ₄	221-224	-152.0	<i>Jungermannia subulata</i>	(629)	
1198	<i>ent</i> -16,17-Epoxykauran-15-one	C ₂₀ H ₃₀ O ₂		-109.0	<i>Jungermannia truncata</i>	(601)	
1199	<i>ent</i> -14 α ,15 α -Dihydroxy-16-karene	C ₂₀ H ₃₂ O ₂		-48.5	<i>Jungermannia truncata</i>	(601)	
1200	<i>ent</i> -20-Acetoxy-11 α -hydroxy-16-kauran-15-one	C ₂₂ H ₃₂ O ₄		-94.0	<i>Jungermannia truncata</i>	(601)	
1201	<i>ent</i> -11 α -Acetoxy-7 β ,14 α -dihydroxy-16-kauran-15-one	C ₂₂ H ₃₂ O ₅		+21.3	<i>Jungermannia truncata</i>	(601)	
1202	(16 <i>R</i>)- <i>ent</i> -3 α -Hydroxykauran-15-one	C ₂₀ H ₃₂ O ₂		-45.1	<i>Jungermannia subulata</i>	(629)	Cell culture
1203	<i>ent</i> -1 β -Hydroxy-9(11),16-kauradien-15-one	C ₂₀ H ₂₈ O ₂	138-140	+238.7	<i>Jungermannia truncata</i>	(601)	
1204	<i>ent</i> -9(11),16-Kauradien-12,15-dione	C ₂₀ H ₂₆ O ₂	114-116	+386.6	Unidentified <i>Jungermannia</i> sp.	(602)	
1205	Jungermannenone A	C ₂₀ H ₂₈ O ₂	105-106	-256.5	Unidentified <i>Jungermannia</i> sp.	(602)	
					Unidentified <i>Jungermannia</i> sp.	(609)	
					Unidentified <i>Jungermannia</i> sp.	(610)	
1206	Jungermannenone B	C ₂₀ H ₂₈ O		-323.3	Unidentified <i>Jungermannia</i> sp.	(609)	
					Unidentified <i>Jungermannia</i> sp.	(610)	
1207	Jungermannenone C	C ₂₀ H ₂₈ O ₂	72-74	-262.2	Unidentified <i>Jungermannia</i> sp.	(609)	
					Unidentified <i>Jungermannia</i> sp.	(610)	

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1208	Jungermannenone D	C ₂₀ H ₂₈ O ₃	166-167	-242.4	Unidentified <i>Jungermannia</i> sp.	(609)	
1209	Jungermannenone E	C ₂₀ H ₂₈ O ₂		-328.6	Unidentified <i>Jungermannia</i> sp.	(610)	
1210	16 α ,17-Dihydrojungermannenone A	C ₂₀ H ₃₀ O ₂	84-85	-18.7	Unidentified <i>Jungermannia</i> sp.	(609)	
1211	ent-16-Kauren-6 β ,15 α -diol	C ₂₀ H ₃₂ O ₂		-62.8	Unidentified <i>Jungermannia</i> sp.	(609)	
1212	ent-16-Kauren-6 β ,11 α ,15 α -triol	C ₂₀ H ₃₂ O ₃			Unidentified <i>Jungermannia</i> sp.	(609)	
1213	(16R)-ent-6 β -Hydroxykaur-15-one	C ₂₀ H ₃₂ O ₂	198-200	-86.8	Unidentified <i>Jungermannia</i> sp.	(609)	X-ray
1214	(16R)-ent-6 β ,11 α -Dihydroxykaur-15-one	C ₂₀ H ₃₂ O ₃	168-169	-73.3	Unidentified <i>Jungermannia</i> sp.	(609)	
1215	8,15- <i>seco</i> -8,16-ent-Kauradien-15-ol	C ₂₀ H ₃₂ O ₂		-33.1	Unidentified <i>Jungermannia</i> sp.	(609)	
1216	ent-11 α ,15 α -Epoxykauran-6 β ,15 α -diol	C ₂₀ H ₃₂ O ₃		-36.2	Unidentified <i>Jungermannia</i> sp.	(609)	X-ray
1217	ent-9(11),16-Kauradien-15 α -ol	C ₂₀ H ₃₀ O	52-54	+74.2	Unidentified <i>Jungermannia</i> sp.	(609)	
1218	ent-9(11),16-Kauradien-15-one	C ₂₀ H ₂₈ O	53	+234.8	Unidentified <i>Jungermannia</i> sp.	(609)	
1219	Jungematrobrunin A	C ₂₄ H ₃₂ O ₈	157-159	+35.0	<i>Jungermannia atrobrunnea</i>	(668)	X-ray
1220	1 α ,6 α -Diacetoxylungermannenone C	C ₂₄ H ₃₂ O ₆	196-197	-36.2	<i>Jungermannia atrobrunnea</i>	(668)	
1221	1 α -Acetoxylungermannenone C	C ₂₂ H ₃₀ O ₅		-34.3	<i>Jungermannia atrobrunnea</i>	(668)	
1222	1 α ,6 α -Diacetoxylungermannenone C	C ₂₄ H ₃₀ O ₆		+42.4	<i>Jungermannia atrobrunnea</i>	(668)	
1223	(16R)-1 α ,6 β -Diacetoxylungermannenone C	C ₂₄ H ₃₂ O ₆		+61.8	<i>Jungermannia atrobrunnea</i>	(668)	
1224	1 α ,6 α -Diacetoxylungermannenone C	C ₂₄ H ₃₂ O ₆	194-197	+51.2	<i>Jungermannia atrobrunnea</i>	(668)	

1225	6 α -Acetoxy-1 α ,12 β -dihydroxy- <i>ent</i> -9(11),16-kauradien-15-one	C ₂₂ H ₃₀ O ₅	+45.2	<i>Jungermannia atrobrunnea</i>	(668)
1226	15 β -Acetoxy-6 α -hydroxy- <i>ent</i> -9(11),16-kauradiene	C ₂₂ H ₃₂ O ₃	-55.0	<i>Jungermannia atrobrunnea</i>	(668)
1227	6 α ,15 β -Diacetoxy- <i>ent</i> -9(11),16-kauradiene	C ₂₄ H ₃₄ O ₄	-46.4	<i>Jungermannia atrobrunnea</i>	(668)
1228	6 α ,15 β -Diacetoxy- <i>ent</i> -9(11),16-kauradien-12-one	C ₂₄ H ₃₂ O ₅	-24.7	<i>Jungermannia atrobrunnea</i>	(668)
1229	14 β -Hydroxy- <i>ent</i> -16-kaurene	C ₂₀ H ₃₂ O		<i>Nardia subclavata</i>	(84)
1230	<i>ent</i> -14 α ,16 β -Dihydroxykaurane	C ₂₀ H ₃₄ O ₂		<i>Nardia subclavata</i>	(84)
1231	(14 <i>R</i>)- <i>ent</i> -Kaur-16-en-14-yl hydrogen malonate	C ₂₃ H ₃₄ O ₄		<i>Nardia subclavata</i>	(84)
1232	(14 <i>R</i>)- <i>ent</i> -Kaur-16-en-14-yl phytyl malonate	C ₄₃ H ₇₂ O ₄		<i>Nardia subclavata</i>	(84)
1233	bis-(14 <i>R</i>)- <i>ent</i> -Kaur-16-en-14-yl malonate	C ₄₃ H ₆₄ O ₄		<i>Nardia subclavata</i>	(84)
1234	Labda-8(17), (12 <i>E</i>), 14-triene	C ₂₀ H ₃₂		<i>Herbertus alpinus</i>	(616) (635)
1235	Labda-8(17), (12 <i>E</i>), 14-trien-6 α -ol	C ₂₀ H ₃₂ O		<i>Herbertus alpinus</i>	(72) (558)
1236	<i>ent</i> -3 β -Hydroxy-8(17), (12 <i>E</i>), 14-labdatriene	C ₂₀ H ₃₂ O		<i>Herbertus alpinus</i>	(558)
1237	(+)-Labda-8(17), 14-diene-(9 <i>R</i> *, 13 <i>S</i> *)-diol	C ₂₀ H ₃₄ O ₂	+34.2	<i>Trichocolea pluma</i>	(153)
		124-125		<i>Jungermannia hattoriana</i>	(590)
				<i>Jungermannia infusca</i>	(591) (595)
1238	Secoinfuscadione	C ₂₀ H ₃₂ O ₂	-3.2	<i>Jungermannia truncata</i>	(569)
				<i>Jungermannia infusca</i>	(591) (595)
1239	Infuscadiol	C ₂₀ H ₃₄ O ₃		<i>Jungermannia infusca</i>	(595)
1240	(13 <i>S</i>)-Hydroxy-8,14-labdadiene	C ₂₀ H ₃₄ O	-7.8	<i>Jungermannia hattoriana</i>	(590)

(continued)

X-ray

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ /° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
					<i>Jungermannia appressifolia</i>	(952)	
					<i>Jungermannia infusca</i>	(595)	
						(600)	
1241	Labda-7,14-dien-13-ol	C ₂₀ H ₃₄ O			<i>Ptychanthus striatus</i>	(957)	
1242	8- <i>epi</i> -Sclareol	C ₂₀ H ₃₆ O ₂			<i>Pleurozia gigantea</i>	(490)	X-ray
1243	13- <i>epi</i> -Sclareol	C ₂₀ H ₃₆ O ₂			<i>Jungermannia hattoriana</i>	(590)	
					<i>Jungermannia infusca</i>	(592)	
						(595)	
						(597)	
					<i>Jungermannia truncata</i>	(569)	
1244	Labda-(12 <i>E</i>),14-dien-7 α ,8 α -diol	C ₂₀ H ₃₄ O ₂			<i>Ptychanthus striatus</i>	(957)	
1245	Ptychantin A	C ₂₆ H ₄₀ O ₈	202-204	-75.3	<i>Porella perrottetiana</i>	(318)	X-ray
					<i>Ptychanthus striatus</i>	(305)	
						(320)	
1246	Ptychantin B	C ₂₈ H ₄₂ O ₉	222-223	-49.3	<i>Ptychanthus striatus</i>	(305)	
						(320)	
1247	Ptychantin C	C ₂₄ H ₃₈ O ₇	213-215	-54.0	<i>Ptychanthus striatus</i>	(305)	
						(320)	
1248	Ptychantin D	C ₂₆ H ₄₀ O ₉	131-132	-68.9	<i>Ptychanthus striatus</i>	(305)	
1249	Ptychantin E	C ₂₄ H ₃₈ O ₇	192-193	-17.4	<i>Ptychanthus striatus</i>	(305)	
1250	Ptychantin F	C ₃₀ H ₄₆ O ₁₁	202-204	-11.1	<i>Ptychanthus striatus</i>	(308)	X-ray
				-2.9		(399)	Cultured cells
1251	Ptychantin G	C ₃₂ H ₄₈ O ₁₂		-6.8	<i>Ptychanthus striatus</i>	(308)	Cultured cells
				-16.7		(399)	
						(957)	
1252	Ptychantin H	C ₂₈ H ₄₄ O ₁₀	169-179	+4.8	<i>Ptychanthus striatus</i>	(308)	

1253	Ptychanthin I	C ₂₈ H ₄₄ O ₉	137-138	+10.9	<i>Ptychanthus striatus</i>	(308) (957)	X-ray
1254	Ptychanthin J	C ₂₆ H ₄₀ O ₉		-61	<i>Ptychanthus striatus</i>	(957)	
1255	Ptychanthin K	C ₂₄ H ₃₈ O ₇		-62.6	<i>Ptychanthus striatus</i>	(957)	
1256	Ptychanthin L	C ₂₆ H ₄₂ O ₇			<i>Ptychanthus striatus</i>	(957)	
1257	Ptychanthin M	C ₂₄ H ₄₀ O ₅		-73.7	<i>Ptychanthus striatus</i>	(957)	
1258	Ptychanthin N	C ₃₀ H ₄₆ O ₁₁			<i>Ptychanthus striatus</i>	(957)	
1259	Ptychanthin O	C ₂₈ H ₄₄ O ₉		-23.1	<i>Ptychanthus striatus</i>	(399)	Cultured cells
1260	Ptychanthin P	C ₂₆ H ₄₀ O ₉	213-214	-127.2	<i>Ptychanthus striatus</i>	(325)	
1261	Ptychanthin Q	C ₂₆ H ₄₀ O ₉		-81.9	<i>Ptychanthus striatus</i>	(325)	
1262	(+)-Isoabienol	C ₂₀ H ₃₄ O			<i>Jungermannia infusca</i>	(591)	
1263	19-Acetoxyisoabienol	C ₂₂ H ₃₄ O ₃			<i>Plagiochila circinalis</i>	(597) (635) (897)	
1264	(4 <i>R</i> *,5 <i>R</i> *,8 <i>R</i> *,9 <i>S</i> *,10 <i>S</i> *)-Labda-13(16),14-dien-8,18-ol	C ₂₀ H ₃₂ O ₂			<i>Plagiochila circinalis</i>	(635) (897)	
1265	(8 <i>S</i> *,13 <i>S</i> *)-Dihydroxy-9(11),14-labdadiene	C ₂₀ H ₃₂ O	113-115	-36.6	<i>Jungermannia infusca</i>	(595)	X-ray
1266	(8 <i>S</i> *)-Hydroperoxy-(13 <i>S</i> *)-hydroxy-9(11),14-labdadiene	C ₂₀ H ₃₂ O ₂		-4.6	<i>Jungermannia infusca</i>	(595)	
1267	(+)-Labda-7,(13 <i>E</i>)-dien-15-ol	C ₂₀ H ₃₄ O		+9.4	<i>Marchantia paleacea</i> var. <i>diptera</i>	(436)	
1268	(13 <i>E</i>)-Labdene-8 <i>α</i> ,15-diol	C ₂₀ H ₃₆ O ₂			<i>Jungermannia infusca</i>	(592)	X-ray
1269	(+)-Gomeraldehyde	C ₂₀ H ₃₄ O ₂			<i>Jungermannia infusca</i>	(592) (597)	
1270	(+)- <i>epi</i> -Gomeraldehyde	C ₂₀ H ₃₄ O ₂			<i>Jungermannia infusca</i>	(592) (597)	
1271	<i>ent</i> -13- <i>epi</i> -Manool	C ₂₀ H ₃₄ O			<i>Jungermannia vulcanicola</i>	(585)	(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1272	<i>ent</i> -8(17),14-Labdadiene-5 α , (13 <i>R</i>)-diol	C ₂₀ H ₃₄ O ₂		-51.4	<i>Jungermannia vulcanicola</i>	(585)	
1273	Labda-7,14-dien-9,13-diol	C ₂₀ H ₃₄ O ₂		+11	<i>Jungermannia appressifolia</i>	(952)	
1274	13-Hydroxy-7-oxolabda-8,14-diene	C ₂₀ H ₃₂ O ₂		+23	<i>Jungermannia appressifolia</i>	(952)	
1275	3-Oxolabda-8(17),13(16),14-triene	C ₂₀ H ₃₀ O		+34.5	<i>Jamesoniella colorata</i>	(340)	
1276	3,11-Dioxolabda-8(17),13(16),14-triene	C ₂₀ H ₂₈ O ₂		+12.1	<i>Jamesoniella colorata</i>	(340)	
1277	3 α -Hydroxy-11-oxolabda-8(17),13(16),14-triene	C ₂₀ H ₃₀ O ₂		+47.0	<i>Jamesoniella colorata</i>	(340)	
1278	3 β -Hydroxy-11-oxolabda-8(17),13(16),14-triene	C ₂₀ H ₃₀ O ₂		+9.8	<i>Jamesoniella colorata</i>	(340)	
1279	3 β -Hydroxylabda-8(17),13(16),14-triene	C ₂₀ H ₃₂ O		+12.1	<i>Jamesoniella colorata</i>	(340)	
1280	11-Hydroxy-3-oxolabda-8(17),13(16),14-triene	C ₂₀ H ₃₀ O ₂		+8.14	<i>Jamesoniella colorata</i>	(340)	
1281	<i>trans</i> -Communic acid (=8(16), (12 <i>E</i>),14-Labdatrien-19-oic acid	C ₂₀ H ₃₀ O ₂			<i>Porella navicularis</i> <i>Plagiochila ovalifolia</i>	(143) (84)	
1282	8(16),(12 <i>Z</i>),14-Labdatrien-19-oic acid	C ₂₀ H ₃₀ O ₂			<i>Marchantia emarginata</i> subsp. <i>tosana</i>	(347)	
1283	<i>ent</i> -Labda-13(16),14-dien-8 β -ol	C ₂₀ H ₃₄ O		-15.7	<i>Blepharostoma trichophyllum</i>	(215)	<i>in vitro</i> Culture
1284	<i>ent</i> -Labda-13(16),14-diene-1 α ,8 β -diol	C ₂₀ H ₃₄ O ₂		-14.7	<i>Blepharostoma trichophyllum</i>	(215)	<i>in vitro</i> Culture
1285	<i>ent</i> -Labda-13(16),14-diene-8 β ,9 α -diol	C ₂₀ H ₃₄ O ₂		-2.8	<i>Blepharostoma trichophyllum</i>	(215)	<i>in vitro</i> Culture
1286	<i>ent</i> -Labda-13(16),14-diene-1 α ,8 β ,9 α -triol	C ₂₀ H ₃₄ O ₄	114	-58.8	<i>Blepharostoma trichophyllum</i>	(215)	<i>in vitro</i> Culture

Number	Chemical name	Formula	mp, °C	Ref.
1287	ent-8 β ,9 α -Dihydroxylabda-13(16),14-dien-1-one	C ₂₀ H ₃₂ O ₃	+13.6	(215)
1288	Labda-14-en-13,9-oxide (=Manoyl oxide)	C ₂₀ H ₃₄ O		(78)
1289	Symphyogynolide	C ₂₀ H ₃₀ O ₄	+38.3	(957)
1290	1 α ,5 α ,8 α -Trihydroxy-(13E)-labden-12-one	C ₂₀ H ₃₄ O ₄	+41.7	(475)
1291	5 α ,8 α ,9 α -Trihydroxy-(13E)-labden-12-one	C ₂₀ H ₃₄ O ₄	−9.3	(843)
1292	5 α ,8 α -Dihydroxy-(13E)-labden-12-one	C ₂₀ H ₃₄ O ₃	+30.3	(973)
1293	Scapaundulin A	C ₃₂ H ₄₈ O ₆	−60.2	(973)
1294	Scapaundulin B	C ₄₀ H ₆₄ O ₆	+48.3	(973)
1295	Pallavicinin	C ₂₀ H ₂₆ O ₄	+12	(468)
			219-221	(490)
				(887)
1296	18-Hydroxypallavicinin	C ₂₀ H ₂₆ O ₅	−5	(954)
			−15.3	(468)
1297	Neopallavicinin	C ₂₀ H ₂₆ O ₄	−209	(887)
			190-192	(468)
1298	8 α -Hydroxy-3-oxo-8(7 $\rightarrow$ 2)abeo-6,(13E)-labdadien-16,11-olide	C ₂₀ H ₂₆ O ₄	−2.9	(475)
1299	(11 α H,12 α H)-8,12-Epoxy-3-oxo-19-nor-8((7 $\rightarrow$ 4)abeo-(1Z,6,13E))-labdatrien-16,11-olide	C ₁₉ H ₂₂ O ₄	−223.0	(887)
1300	(11 β H,12 β H)-8,12-Epoxy-3-oxo-19-nor-8((7 $\rightarrow$ 4)abeo-6,(13E)-labdadien-16,11-olide	C ₁₉ H ₂₂ O ₄	−35.4	(702)

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1301	3,8-Dioxo-7,8- <i>seco</i> -1(12),2(15)-bicyclo-6,(13 <i>E</i>)-labdadien-16,11-olide	C ₂₀ H ₂₄ O ₄		-34.2	<i>Pallavicinia subciliata</i>	(887)	
1302	3,8-Dioxo-7,8- <i>seco</i> -1(12),2(15)-bicyclo-18- <i>nor</i> -6,(13 <i>E</i>)-labdadien-16,11-olide	C ₁₉ H ₂₂ O ₄		-29.6	<i>Pallavicinia subciliata</i>	(887)	
1303	3,8-Dioxo-7,8- <i>seco</i> -1(12),2(15)-bicyclo-19- <i>nor</i> -6,(13 <i>E</i>)-labdadien-16,11-olide	C ₁₉ H ₂₂ O ₄		+8.0	<i>Pallavicinia subciliata</i>	(702)	
1304	2- <i>Epi</i> -3,8-dioxo-7,8- <i>seco</i> -1(12),2(15)-bicyclo-19- <i>nor</i> -6,(13 <i>E</i>)-labdadien-16,11-olide	C ₁₉ H ₂₂ O ₄		-145.7	<i>Pallavicinia subciliata</i>	(887)	
1305	1β,8:8α,12-Diepoxy-3-oxo-7,8- <i>seco</i> -6,(13 <i>E</i>)-labdadien-11,16-olide	C ₁₉ H ₂₄ O ₅		+21.9	<i>Pallavicinia subciliata</i>	(702)	
1306	6β-Acetoxy-5α,7α-dihydroxy-8α,12-epoxy-3-oxo-(13 <i>E</i>)-labden-16,11-olide	C ₂₂ H ₃₀ O ₈		+92.6	<i>Pallavicinia subciliata</i>	(702)	
1307	6β-Acetoxy-5α-hydroxy-8α,12-epoxy-3-oxo-(13 <i>E</i>)-labden-16,11-olide	C ₂₂ H ₃₀ O ₇		+95.1	<i>Pallavicinia subciliata</i>	(702)	
1308	Pleurozoiol	C ₂₀ H ₃₆ O ₂			<i>Jungermannia truncata</i> <i>Pleurozia gigantea</i>	(136) (490)	
1309	8,12:13,14-Diepoxylabda-1-en-3-one (=Musicolone)	C ₂₀ H ₃₀ O ₃	147-149 142-143	+2.3	<i>Frullania hamatiloba</i> <i>Frullania muscicola</i>	(316) (484)	
1310	8,12:13,14-Diepoxylabda-3-one	C ₂₀ H ₃₂ O ₃			<i>Frullania hamatiloba</i>	(316)	
1311	8,12:13,14-Diepoxylabda-1β-ol-3-one	C ₂₀ H ₃₂ O ₄			<i>Frullania hamatiloba</i>	(316)	
1312	3α-Acetoxy- <i>ent</i> -labda-8(17), (12 <i>E</i>),14-trien-19-ol	C ₂₂ H ₃₄ O ₃		-3.9	<i>Jamesoniella autumnalis</i>	(811)	

1313	3 α -Acetoxy- <i>ent</i> -labda-8(17), (12 <i>E</i>),14-triene	C ₂₂ H ₃₄ O ₂	-29.4	<i>Jamesoniella autumnalis</i>	(811)
1314	3 α -Hydroxy- <i>ent</i> -labda-8(17), (12 <i>E</i>),14-trien-18-ol	C ₂₀ H ₃₀ O	-16.2	<i>Jamesoniella autumnalis</i>	(811)
1315	19-Acetoxy- <i>ent</i> -labda-8(17), (12 <i>E</i>),14-trien-3 α -ol	C ₂₂ H ₃₄ O ₃		<i>Jamesoniella autumnalis</i>	(811)
1316	Phytol	C ₂₀ H ₄₀ O		<i>Cyathodium foetidissimum</i>	(494)
				<i>Dumortiera hirsuta</i>	(96)
					(876)
				<i>Gymnocolea inflata</i>	(882)
				<i>Jungermannia fusiformis</i>	(882)
				<i>Jungermannia subulata</i>	(629)
				<i>Metacalpogeia cordifolia</i>	(882)
				<i>Metzgeria temperata</i>	(882)
				<i>Pallavicinia levierii</i>	(882)
				<i>Pellia epiphylla</i>	(175)
					(176)
					(492)
				<i>Plagiochasma japonica</i>	(459)
				<i>Plagiochasma rupestre</i>	(97)
				<i>Plagiochila elegans</i>	(470)
				<i>Plagiochila ovalifolia</i>	(529)
				<i>Porella platyphylla</i>	(583)
				<i>Riccardia nagasakiensis</i>	(141)
				<i>Riccardia palmata</i>	(882)
				<i>Ricciocarpos natans</i>	(974)
				<i>Scapania undulata</i>	(577)
				<i>Schiffneria hyalina</i>	(882)
				<i>Trichocolea pluma</i>	(494)
				<i>Pellia epiphylla</i>	(176)
1317	12,14-Dihydroxyphytol	C ₂₀ H ₄₀ O ₃	± 0		

Sporophytes
& spores

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ ° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1318	(1,2)-Bis- <i>nor</i> -phytone	C ₁₈ H ₃₆ O			<i>Pellia epiphylla</i>	(175)	Sporophytes & spores
1319	Geranyl geraniol	C ₂₀ H ₃₄ O			<i>Pellia epiphylla</i>	(176)	
1320	Phytadienes	C ₂₀ H ₃₈			<i>Plagiochila elegans</i>	(470)	
1321	(2 <i>Z</i>)-Phytene-1,15,20-triol	C ₂₀ H ₄₀ O ₃			<i>Tylimanthus renifolius</i>	(213)	
1322	1,10,14-Phytatrien-6,7-epoxy-3-ol	C ₂₀ H ₃₄ O ₂			<i>Jamesoniella tasmanica</i>	(72)	
1323	Naviculide	C ₂₀ H ₃₀ O ₃			<i>Porella navicularis</i>	(616)	
1324	13- <i>epi</i> -Pimaric-9(11),15-dien-20-oic acid	C ₂₀ H ₃₀ O ₂			<i>Cuspidatula monodon</i>	(143) (72)	
1325	<i>ent</i> -Pimaric-8(14),15-dien-19-oic acid	C ₂₀ H ₃₀ O ₂			<i>Bazzania novae-zelandiae</i>	(616) (615)	
					<i>Dendromastigophora flagellifera</i>	(72)	
					<i>Dendromastigophora</i> sp.	(615)	
					<i>Herbertus sakuraii</i>	(323) (365)	
					<i>Jungermannia hattoriana</i>	(590)	X-ray
					<i>Mastigophora diclados</i>	(287) (425)	
1326	Oblongifolic acid	C ₂₀ H ₃₀ O ₂			<i>Jamesoniella kirkii</i>	(84) (612)	X-ray
1327	<i>ent</i> -Isopimaric-7(8),15-dien-19-ol	C ₂₀ H ₃₂ O			<i>Jamesoniella kirkii</i>	(84)	
1328	1 α -Hydroxy- <i>ent</i> -sandaracopimaric-8(14),15-diene	C ₂₀ H ₃₂ O		+4	<i>Trichocolea mollissima</i>	(612) (483)	
1329	(1 <i>R</i> ,2 <i>R</i>)- <i>ent</i> -1,2-Dihydroxyisopimaric-8(14),15-diene	C ₂₀ H ₃₂ O ₂	132-133	-16.5	<i>Trichocolea mollissima</i>	(605) (605)	X-ray

1330	(2 <i>R</i>)- <i>ent</i> -2-Hydroxyiosopimar-8(14),15-diene	C ₂₀ H ₃₂ O	104-105	-9.6	<i>Trichocolea mollissima</i>	(605)
1331	Sandaracopimaradiene	C ₂₀ H ₃₂			<i>Porella navicularis</i>	(143)
1332	Sandaracopimaric acid	C ₂₀ H ₃₀ O ₂			<i>Mastigophora dichados</i>	(287)
1333	Acanthoic acid	C ₂₀ H ₃₀ O ₂			<i>Plagiochila deltoidea</i>	(607)
1334	Pimara-9(11),15-dien-19-ol	C ₂₀ H ₃₂ O			<i>Jungermannia truncata</i>	(136)
1335	Pimara-9(11),15-dien-2-one	C ₂₀ H ₃₀ O		+285.7	<i>Chiloscyphus mittelmanus</i>	(347)
1336	Rosa-5,15-diene	C ₂₀ H ₃₂			<i>Porella navicularis</i>	(143)
1337	11 β -Hydroxyrosa-5,15-diene	C ₂₀ H ₃₂ O		+50.4	<i>Gackstroemia decipiens</i>	(251)
1338	11 β -Hydroxy-7-oxorosa-5,15-diene	C ₂₀ H ₃₀ O ₂		+76	<i>Gackstroemia decipiens</i>	(251)
1339	1 α ,5 β ,11 β -Trihydroxy-7-oxorosa-15-ene	C ₂₀ H ₃₂ O ₄		+76	<i>Gackstroemia decipiens</i>	(251)
1340	5 β -Hydroxyros-15-ene	C ₂₀ H ₃₄ O		+71	<i>Gackstroemia decipiens</i>	(251)
1341	5 β ,11 β -Dihydroxyros-15-ene	C ₂₀ H ₃₄ O		+68	<i>Gackstroemia decipiens</i>	(251)
1342	5 β ,12 β -Dihydroxyros-15-ene	C ₂₀ H ₃₄ O ₂		+57	<i>Gackstroemia decipiens</i>	(251)
1343	5 β ,20-Epoxy-20-hydroxyros-15-ene	C ₂₀ H ₃₂ O ₂		+35	<i>Gackstroemia decipiens</i>	(251)
1344	5 β ,20-Epoxy-20-methoxyros-15-ene	C ₂₁ H ₃₂ O ₂		+33	<i>Gackstroemia decipiens</i>	(251)
1345	5,15-Rosadiene-3,11-dione	C ₂₀ H ₂₈ O ₂		+40.3	<i>Tylimanthus renifolius</i>	(213)
1346	(3 <i>R</i>)- <i>ent</i> -1(10),15-Rosadien-3-ol	C ₂₀ H ₃₂ O		+3.9	<i>Plagiochila deltoidea</i>	(607)
1347	(3 <i>R</i> ,15 <i>R</i>)- <i>ent</i> -15,16-Epoxy-1(10)-rosen-3-ol	C ₂₀ H ₃₂ O ₂		-4.9	<i>Plagiochila deltoidea</i>	(607)
1348	Sacculatal (=7,17-Sacculatadien-11,12-dial)	C ₂₀ H ₃₀ O ₂		-14.2	<i>Fossombronina alascana</i>	(339)
					<i>Fossombronina wondraczeki</i>	(216)
					<i>Pellia endiviifolia</i>	(311)
						(492)
1349	Isosacculatal	C ₂₀ H ₃₀ O ₂			<i>Pellia epiphylla</i>	(492)
					<i>Pellia endiviifolia</i>	(311)
						(492)
					<i>Pellia epiphylla</i>	(492)

(continued)

X-ray
X-ray
Axenic
culture

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ /° cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1350	1 β -Hydroxysacculatal	C ₂₀ H ₃₀ O ₃	104-105	+49.9	<i>Pellia endiviifolia</i>	(311)	
1351	1 β -Hydroxyisosacculatal	C ₂₀ H ₃₀ O ₃		-71.1	<i>Pellia endiviifolia</i>	(311)	
1352	8(12),17-Sacculatadien-11-ol	C ₂₀ H ₃₂ O		-13	<i>Pellia epiphylla</i>	(176)	
1353	7,17-Sacculatadien-11-acid	C ₂₀ H ₃₂ O ₂		+26	<i>Pellia epiphylla</i>	(176)	
1354	Perrottetianal A	C ₂₀ H ₃₀ O ₂			<i>Lepidozia microphylla</i>	(72)	
					<i>Makinoa crispata</i>	(616)	
					<i>Paraschistochila pinnatifolia</i>	(492)	
					<i>Plagiochila ovalifolia</i>	(84)	
					<i>Porella acutifolia</i> subsp. <i>tosana</i>	(701)	
						(72)	
						(315)	
					<i>Porella elegantula</i>	(322)	
					<i>Porella grandiloba</i>	(616)	
					<i>Porella perrottetiana</i>	(814)	
					<i>Porella grandiloba</i>	(424)	
					<i>Porella platyphylla</i>	(814)	
						(138)	
						(583)	
					<i>Marchantia foliacea</i>	(347)	
				-20.3	<i>Fossombronina wondraczeki</i>	(216)	Axenic culture
					<i>Pellia endiviifolia</i>	(492)	
					<i>Pellia epiphylla</i>	(492)	
					<i>Fossombronina wondraczeki</i>	(216)	Axenic culture
					<i>Fossombronina wondraczeki</i>	(216)	Axenic culture
				-15.7	<i>Pellia endiviifolia</i>	(492)	
					<i>Pellia epiphylla</i>	(492)	
1355	Perrottetianal B (=15 ξ -Hydroxyperrottetianal A)	C ₂₀ H ₃₀ O ₃					
1356	Perrottetianal C	C ₂₀ H ₃₀ O ₃					
1357	Sacculatanolide (=7,17-Sacculatadien-12,11-olide)	C ₂₀ H ₃₀ O ₂					
1358	17,18-Epoxy-7-sacculaten-12,11-olide	C ₂₀ H ₃₀ O ₃					
1359	7,17-sacculatadien-11,12-olide	C ₂₀ H ₃₀ O ₂					

1360	11 β ,12-Epoxy-7,17-sacculatadien-11 α -ol	C ₂₀ H ₃₂ O ₂	-6.3	<i>Fossombronía wondraczeki</i>	(216)	Axenic culture
1361	1 β -Acetoxy-11 β ,12-epoxy-7,17-sacculatadien-11 α -ol	C ₂₂ H ₃₄ O ₄	-8.7	<i>Fossombronía wondraczeki</i>	(216)	Axenic culture
1362	1 β ,15 ξ -Diacetoxy-11,12-epoxy-8(12),9(11),17-sacculatriene	C ₂₄ H ₃₄ O ₅	-46.5	<i>Fossombronía wondraczeki</i>	(216)	Axenic culture
1363	11 β ,12-epoxy-7,17-sacculatadien-1 β ,11 α -diol	C ₂₀ H ₃₂ O ₃	+13.8	<i>Pellia endiviifolia</i>	(311)	X-ray
1364	11 α -Hydroxysacculatanolide	C ₂₀ H ₃₀ O ₃	-49.3	<i>Pellia endiviifolia</i>	(311)	X-ray
1365	1 β -Hydroxysacculatanolide	C ₂₀ H ₃₀ O ₃	-20.3	<i>Pellia endiviifolia</i>	(311)	
1366	1 β ,11 α -Dihydroxysacculatanolide	C ₂₄ H ₃₈ O ₇	-12.5	<i>Pellia endiviifolia</i>	(311)	
1367	Pellianolactone A	C ₂₂ H ₃₂ O ₆	-1.7	<i>Pellia endiviifolia</i>	(311)	
1368	Pellianolactone B	C ₂₂ H ₃₂ O ₅	+14.1	<i>Pellia endiviifolia</i>	(311)	
1369	Pellianolactone C	C ₂₁ H ₃₀ O ₄	+5.58	<i>Pellia endiviifolia</i>	(312)	
1370	Pellianolactol	C ₂₁ H ₃₀ O ₅	-19.64	<i>Pellia endiviifolia</i>	(312)	
1371	11,12-epoxy-8(12),9(11),17-sacculatriene	C ₂₀ H ₃₀ O	+33.43	<i>Pellia endiviifolia</i>	(312)	
1372	11 β ,12-epoxy-17-sacculaten-11 α -ol	C ₂₀ H ₃₄ O ₂	+20.96	<i>Pellia endiviifolia</i>	(312)	
1373	Sacculaporellin	C ₂₀ H ₃₂ O ₂		<i>Pellia epiphylla</i>	(176)	
1374	(13S)-15 ξ -Hydroxysacculaporellin (= (5S,9S,10R,13S)-11,13-epoxy-8(12),17-sacculadiene-13 β ,15 ξ -diol)	C ₂₀ H ₃₂ O ₃	130-135	<i>Porella platyphylla</i>	(138)	
1375	8(12),17-Sacculatadien-11,13-olide	C ₂₀ H ₃₀ O ₂		<i>Paraschistochila pinnatifolia</i>	(84)	
1376	(6R*,9R*,10S*)-3 α ,4 α -Epoxy-18-hydroxyphenoloba-(13E(15),16E)-diene	C ₂₀ H ₃₂ O ₂	-14.0	<i>Anastrophyllum auritum</i> <i>Anastrophyllum donnianum</i>	(976) (139)	

(continued)

Table 4.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1377	3 α ,4 α -Epoxy-5 α ,18-dihydroxy-sphenoloba-(13E(15),16E)-diene	C ₂₀ H ₃₂ O ₃		+21.4	<i>Anastrophyllum auritum</i>	(976)	
1378	3 α ,4 α -Epoxy-18-hydroxy-sphenoloba-(13Z(15),16E)-diene	C ₂₀ H ₃₂ O ₂		-25.2	<i>Anastrophyllum auritum</i>	(976)	
1379	3 α ,4 α -Epoxy-5 α ,18-dihydroxy-sphenoloba-(13Z(15),16E)-diene	C ₂₀ H ₃₂ O ₃		-13.7	<i>Anastrophyllum auritum</i>	(976)	
1380	3 α ,4 α -Epoxysphenoloba-(13E(15),16E,18)-triene	C ₂₀ H ₃₀ O		-55.4	<i>Anastrophyllum auritum</i>	(976)	
1381	3 α ,4 α -Epoxy-5 α -hydroxysphenoloba-(13E(15),16E,18)-triene	C ₂₀ H ₃₀ O ₂	82-83	+12.0	<i>Anastrophyllum auritum</i>	(976)	
1382	3 α ,4 α -Epoxy-5 α -hydroxysphenoloba-13, (15E), 17-triene	C ₂₀ H ₃₀ O ₂	79-80	+30.0	<i>Anastrophyllum auritum</i>	(976)	
1383	(6R*,9R*,10S*)-3 α ,4 α -epoxy-sphenoloba-(13E(15),17)-diene	C ₂₀ H ₃₂ O		+15.7	<i>Anastrophyllum auritum</i>	(976)	
1384	(3R*,6R*,9R*,10S*)-Sphenoloba-(13E(15),16E,18)-trien-4-one	C ₂₀ H ₃₀ O			<i>Anastrophyllum donnianum</i>	(139)	
1385	(3R*,6R*,9R*,10S*)-18-Hydroxysphenoloba-(13E(15),16E)-dien-4-one	C ₂₀ H ₃₂ O ₂			<i>Anastrophyllum donnianum</i>	(139)	
1386	(3R*,6R*,9R*,10S*)-Sphenoloba-(13E(15),17)-dien-4-one	C ₂₀ H ₃₂ O			<i>Anastrophyllum donnianum</i>	(139)	
1387	(6R*,9R*,10S*)-3 α ,4 α -Epoxysphenoloba-13(14), (16E)-dien-15,18-diol	C ₂₀ H ₃₂ O ₃			<i>Anastrophyllum donnianum</i>	(139)	

1388	<i>ent</i> -Trachyloban-18-oic acid	C ₂₀ H ₃₀ O ₂	132-134	-36	<i>Chiloscyphus mittenianus</i> (347)
1389	<i>ent</i> -Trachyloban-19-oic acid	C ₂₀ H ₃₀ O ₂	125-127	-52	<i>Mastigophora diclados</i> (464)
1390	<i>ent</i> -18-Hydroxytrachyloban-19-oic acid	C ₂₀ H ₃₀ O ₃	180-182	-57	<i>Mastigophora diclados</i> (464)
1390a	<i>ent</i> -3 β ,18-Dihydroxytrachyloban-19-oic acid	C ₂₀ H ₃₀ O ₄			<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (40)
1390b	<i>ent</i> -3 β -Hydroxytrachylobane	C ₂₀ H ₃₂ O		-44.1	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390c	<i>ent</i> -Trachyloban-3-one	C ₂₀ H ₃₀ O		-19.6	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390d	<i>ent</i> -3 β -Acetoxytrachylobane	C ₂₂ H ₃₄ O ₂		-39.4	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390e	<i>ent</i> -3 β -Acetoxy-18-hydroxy-trachylobane	C ₂₂ H ₃₄ O ₃		-11.3	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390f	<i>ent</i> -18 α -Acetoxy-3 β -hydroxy-trachylobane	C ₂₂ H ₃₄ O ₃		-15.5	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390g	<i>ent</i> -3 β -Acetoxy-19-hydroxy-trachylobane	C ₂₂ H ₃₄ O ₃		-27.0	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390h	<i>ent</i> -3 β -Acetoxytrachyloban-18-al	C ₂₂ H ₃₂ O ₃		-27.4	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390i	<i>ent</i> -3 β -Acetoxytrachyloban-19-al	C ₂₂ H ₃₂ O ₃		-33.4	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390j	<i>ent</i> -3 β -Acetoxy-17-hydroxy-trachylobane	C ₂₂ H ₃₄ O ₃		-29.2	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390k	<i>ent</i> -17-Hydroxytrachylobane	C ₂₀ H ₃₂ O		-62.7	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390l	<i>ent</i> -Trachyloban-17-al	C ₂₂ H ₃₀ O		-14.3	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390m	<i>ent</i> -3 β ,18-Diacetoxy-19-trachylobanoic acid	C ₂₂ H ₃₄ O ₂			<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)
1390n	<i>ent</i> -3 β ,18 α -Dihydroxytrachylobane	C ₂₀ H ₃₂ O ₂		-24.0	<i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> (717)

(continued)

Table 4.3 (continued)

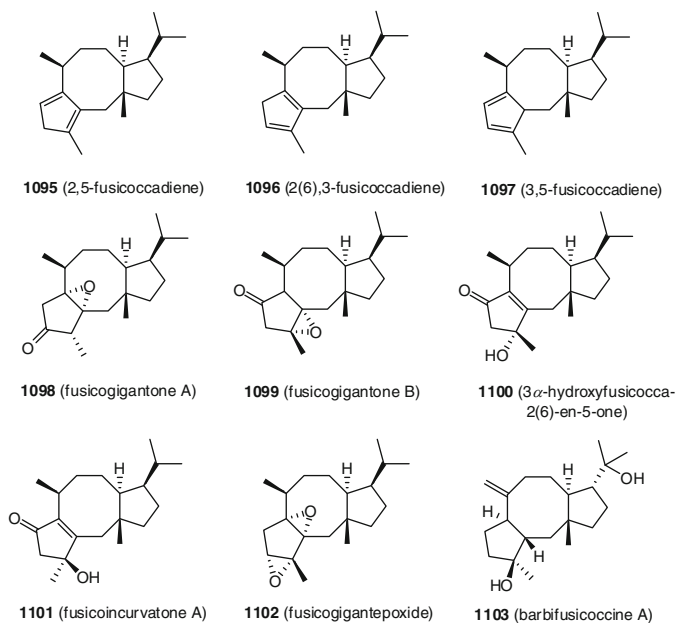
Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1390b	<i>ent</i> -3 β -Hydroxy-17-trachylobanoic acid	C ₂₀ H ₃₀ O ₃		-35.2	<i>Jungmannia exsertifolia</i>	(717)	
1391	<i>ent-exo</i> -Verticillene	C ₂₀ H ₃₂			subsp. <i>cordifolia</i>	(614)	
1392	<i>ent</i> -Verticillo	C ₂₀ H ₃₂ O		-106.3	<i>Jackiella javanica</i>	(421)	
					<i>Chandonanthus hirtellus</i>	(423)	
						(494)	
					<i>Jackiella javanica</i>	(587)	
						(608)	
1393	<i>ent</i> -12- <i>epi</i> -Verticillo	C ₂₀ H ₃₂ O		-141.6	Unidentified <i>Jungmannia</i> sp.	(494)	
					<i>Chandonanthus hirtellus</i>	(423)	
						(494)	
					<i>Jackiella javanica</i>	(587)	
						(608)	
1394	<i>ent</i> -Isoverticillenol	C ₂₀ H ₃₂ O		-116.5	<i>Jackiella javanica</i>	(587)	
1395	<i>ent</i> -Verticilla-3,7,12-trien-1 β -ol	C ₂₀ H ₃₂ O	93-95	-208.9	<i>Jackiella javanica</i>	(608)	X-ray
1396	<i>ent</i> -Verticillanediol	C ₂₀ H ₃₂ O ₂		-97.5	<i>Jackiella javanica</i>	(587)	X-ray
1397	<i>ent</i> -12- <i>epi</i> -Verticillanediol	C ₂₀ H ₃₂ O ₂		-115.7	<i>Jackiella javanica</i>	(608)	
1398	(1S,12S)- <i>ent</i> -1-Hydroxyverticilla-(3E,7E)-dien-18-al	C ₂₀ H ₃₂ O ₂		-50.5	<i>Jackiella javanica</i>	(587)	
1399	(6S,12R)- <i>ent</i> -Verticilla-3,7-dien-6,12-diol	C ₂₀ H ₃₄ O ₂		-86.2	<i>Jackiella javanica</i>	(614)	
1400	(1S,3R,4R)- <i>ent</i> -3,4-Epoxyverticilla-7,12(18)-dien-1-ol	C ₂₀ H ₃₂ O ₂		-86.2	<i>Jackiella javanica</i>	(614)	

							X-ray
1401	(7 <i>R</i> ,8 <i>R</i> ,12 <i>R</i>)- <i>ent</i> -7,8-Epoxy-(3 <i>E</i>)- verticillen-12-ol	C ₂₀ H ₃₄ O ₂	157-158	-114.2		<i>Jackiella javanica</i>	(608)
1402	(7 <i>R</i> ,8 <i>R</i> ,12 <i>S</i>)- <i>ent</i> -7,8-Epoxy-(3 <i>E</i>)- verticillen-12-ol	C ₂₀ H ₃₄ O ₂	86-87	-137.8		<i>Jackiella javanica</i>	(608)
1403	(5 <i>S</i>)- <i>ent</i> -Verticilla-(3 <i>E</i> ,7 <i>E</i> ,12(18))- trien-5-ol	C ₂₀ H ₃₂ O	116-117	-150.8		<i>Jackiella javanica</i>	(608)
1404	Denudatenone A	C ₂₀ H ₃₂ O ₂		+222.0		<i>Odontoschisma denudatum</i>	(316)
1405	Denudatenone B	C ₂₀ H ₃₀ O ₂		+375.5		<i>Odontoschisma denudatum</i>	(319)
1406	Denudatenone C	C ₂₀ H ₃₀ O ₂		+64.3		<i>Odontoschisma denudatum</i>	(316)
1407	Denudatenone D	C ₂₀ H ₃₀ O ₂				<i>Odontoschisma denudatum</i>	(319)
1408	Denudatenone E	C ₂₀ H ₃₀ O ₂				<i>Odontoschisma denudatum</i>	(316)
1409	Neodenudatenone A	C ₂₀ H ₃₀ O ₂		+73.1		<i>Odontoschisma denudatum</i>	(317)
1410	Neodenudatenone B	C ₂₀ H ₃₂ O ₂		-11.0		<i>Odontoschisma denudatum</i>	(317)
1411	Viscida-3,9,14-triene	C ₂₀ H ₃₂				<i>Radula perrottetii</i>	(826)
1412	Viscida-3,11(18),14-triene	C ₂₀ H ₃₂				<i>Radula perrottetii</i>	(826)
1413	Atisane-type 1	C ₂₂ H ₃₂ O ₆		-54		<i>Lepidolaena clavigera</i>	(655)
1414	Atisane-type 2	C ₂₂ H ₃₂ O ₅		-47		<i>Lepidolaena clavigera</i>	(655)
1415	(+)-Viticolol	C ₂₀ H ₃₂ O				<i>Saccogyna viticulosa</i>	(276)
1416	Infuscatrienol	C ₂₀ H ₃₄ O		+29.2		<i>Jungmannia infusca</i>	(584)
							(587)
							(598)
1417	Makinin	C ₂₁ H ₂₆ O ₃		-71		<i>Makinoa crispata</i>	(474)
1418	Pellialactone	C ₁₉ H ₂₆ O ₃		-117		<i>Pellia epiphylla</i>	(176)
1419	Hatcherenone	C ₂₀ H ₃₂ O ₂		+27.4		<i>Barbilophozia hatcheri</i>	(593)

Nagashima and colleagues reported that the Swiss *Barbilophozia lycopodioides* and the Finnish *B. barbata* elaborate barbifusicoccin A (**1103**) and/or barbi-fusicoccin B (**1104**) (583, 596). The structures of compounds **1103** and **1104** were elucidated by considering their ^1H -, ^{13}C -, and 2D-NMR spectra and by comparison with NMR data of the same compounds previously isolated from *B. floerkei* (40).

The ether extract of the Ecuadorian *Anastrophyllum auritum* was fractioned by CC, MPLC, and HPLC to give a new fusicoccane diterpenoid named fusicoauriton (**1107**) (976). The same compound **1107** was also isolated from *Chandonanthus hirtellus* collected in Tahiti (423). The spectroscopic data of **1107**, along with the co-occurrence of the known fusicogigantone A (**1098**) and fusicogigantone B (**1099**), was used for the structural determination of this fusicoccane-type diterpenoid. However, the relative configuration at C-6 has remained uncertain. The same compound was also isolated from the Chilean *Lepicolea ochroleuca* (478).

Chandonanthus hirtellus, collected in Tahiti, was extracted with ether and methanol. Extracts were purified by CC to give the two new fusicoccanes **1108** and **1109** together with the known fusicogigantone A (**1098**), fusicogigantone B (**1099**), fusicogigantepoxide (**1102**), anadensin (**1105**), and fusicoauriton (**1107**). The structures of **1108** and **1109** were assigned as fusicoauriton 6 α -methyl ether and 6 β ,10 β -epoxy-5 β -hydroxyfusicocc-2-ene by comparison of their spectroscopic data with those of fusicoauriton (**1107**) (422, 423).

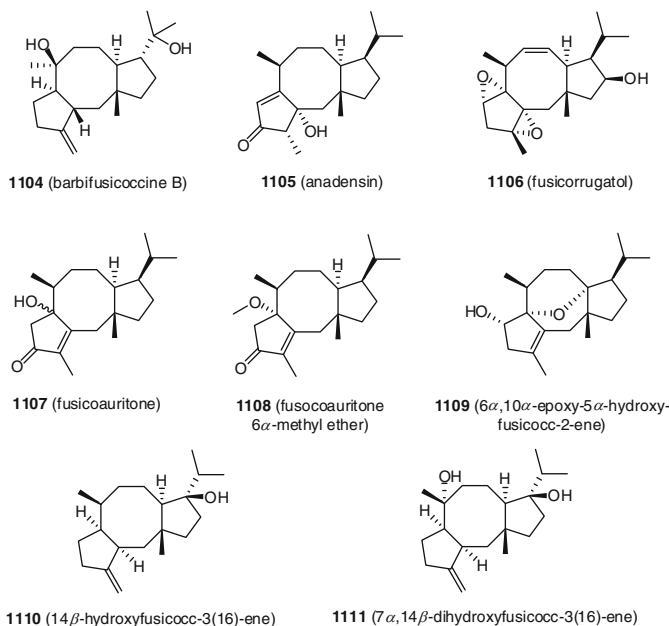


Fusicoccane-type diterpenoids found in the Marchantiophyta

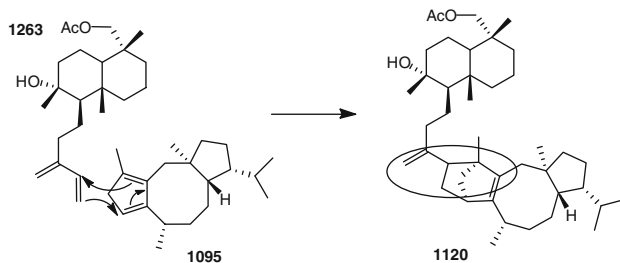
Hashimoto and associates found that *Plagiochila sciophila* produces not only dolabellane (**1094**) but also the fusicoccane 14 β -hydroxyfusicocc-3(16)-ene (**1110**) and 7 α ,14 β -dihydroxyfusicocc-3(16)-ene (**1111**), with their structures determined by 2D-NMR analysis (326).

Plagiochila ovalifolia is an interesting liverwort chemically since it elaborates not only a number of 2,3-*seco*-aromadendranes, as mentioned in Sect. 4.2.4, but also several fusicoccane named fusicoplugins A-I (**1112–1119**). All of these structures were proposed by comparison of their spectroscopic data with those of the previously isolated fusicoccane from other *Plagiochila* species (701).

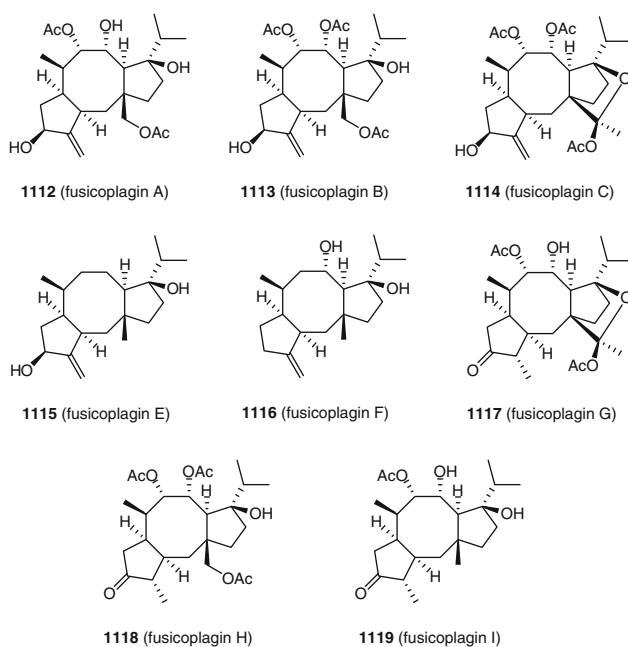
Fractionation of the ether extract of the New Zealand *Plagiochila cricinalis* afforded the three new labdane-fusicoccane dimeric compounds **1120**, **1121**, and **1122**. The structures of these compounds were elucidated by careful analysis of their 2D-NMR spectra, and their relative configurations were analyzed by MOE using MMFF94 parameters. The results obtained from a NOESY experiment were supportive of those deduced by MOE calculations. The monomeric labdane **1263** was found to co-occur in this same *P. cricinalis* specimen with 2,5-fusicoccadiene (**1095**), which is a common diterpene hydrocarbon found in liverworts. Thus, the labdane-fusicoccane dimers **1120**, **1121**, and **1122** might be formed by a *Diels-Alder*-like reaction, as shown in Scheme 4.39 (635). Similar eudesmane/fusicoccane dimers have been isolated from the Panamanian liverwort, *Plagiochila moritziana* (40). This represents the first isolation of labdane-fusicoccane dimers from the liverworts.



Fusicoccane-type diterpenoids found in the Marchantiophyta

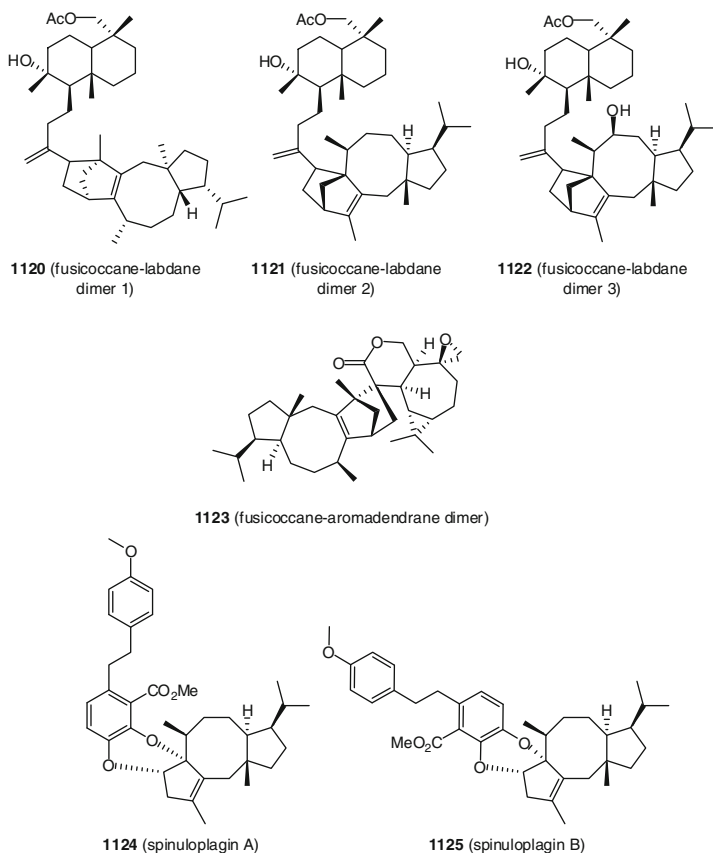


Scheme 4.39 Formation of a labdane-fusicoccane dimer by a *Diels-Alder*-like reaction



Fusicoccane-type diterpenoids found in the Marchantiophyta

Further purification of the ether extract of *P. yokogurensis* led to the isolation of the new dimeric 2,3-secoaromadendrane/fusicoccane dimer **1123**, together with plagiochiline C (**185**) and plagiochilide (**203**) (84). The Scottish *Plagiochila spinulosa* also contains the previously known spinuloplagnin A (**1124**) and spinuloplagnin B (**1125**) (40), together with anadensin (**1105**) (617).

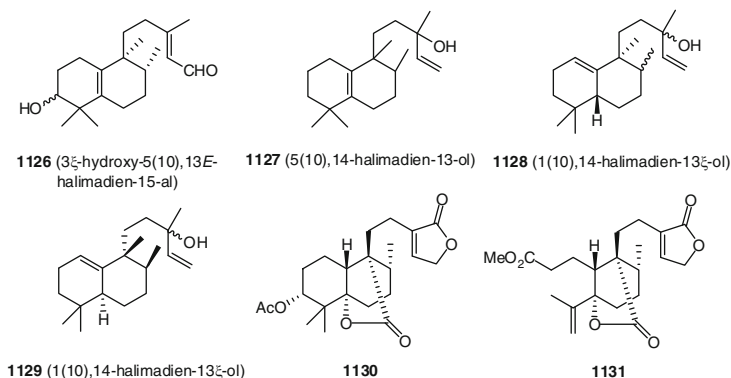


Fusicoccane-type diterpenoids found in the Marchantiophyta

4.3.6 Halimanes

The distribution of halimanes in the liverworts is limited to a few *Jungermanniales* species. The ether extract of the German *Jungermannia hyalina* was fractionated by HPLC to afford the new halimane diterpenoid **1126**. From NMR spectra inclusive of those obtained by COSY, HMBC, and NOESY experiments, a halimane structure for **1126** was deduced. The stereochemistry of the hydroxy group at C-3 was presumed to be *equatorial* from the coupling constant (*dd*, $J = 10.7, 4.2$ Hz) of H-3. The α -orientations of Me-17 and Me-20 were suggested on the basis of the co-occurrence of the clerodane diterpenoids **987–989** in the

same plant. Thus, the structure of **1126** was postulated as 3 ξ -hydroxy-5(10),(13*E*)-halimadien-15-al (**580**). This was the third report of a halimane diterpenoid from a liverwort (**40**).



Halimane-type diterpenoids found in the Marchantiophyta

Jungermannia infusca produces not only clerodanes but also the halimane diterpene 5(10),14-halimadien-13-ol (**1127**), for which its structure was based on 2D-NMR experiments (**600**). 1(10)-Halimadien-13 ξ -ol (**1128**) was isolated from the ether extract of *Jungermannia infusca* and its structure elucidated using COSY, HMQC, HMBC, and NOESY experiments. However, the stereochemistry at C-8 and the hydroxy group orientation at C-13 remained to be clarified (**598**).

The ether extract of *Plagiochila barteri* was purified by CC to give 1(10),14-halimadien-13 ξ -ol (**1129**), for which the structure was assigned by comparison of its spectroscopic data with those of 1(10),14-halimadien-7H ξ ,13 ξ -ol (**1128**), obtained from the another liverwort, *Jungermannia infusca* (**598**). Compounds **1129** and **1128** were differentiated by their optical rotation values ($[\alpha]_D +28.2$ and $-60.2^\circ\text{cm}^2\text{g}^{-1}10^{-1}$), suggesting that they are enantiomeric. However, the difference in optical rotation values between these compounds may be also interpreted as being due to the configurational difference at C-13 (**295**).

Heteroscyphus planus elaborates mainly clerodane-type diterpenoids (**310**, **560**, **561**). Further fractionation of the ether extract of *H. coalitus* over silica gel and Sephadex LH-20 resulted in the isolation of the two new lactones, halimane dilactone (**1130**) and 3,4-*seco*-halimane dilactone (**1131**). The halimane skeleton of **1130** was deduced by 2D-NMR spectroscopic data interpretation, and conclusive evidence for the structure was furnished by the X-ray crystallographic analysis of **1130**. The structure of **1131** was proposed by comparison of its spectroscopic data with those of **1130** and from detailed analysis of relevant 2D-NMR experiments (**873**).

4.3.7 Kauranes

Members of the genus *Jungermannia* are rich sources of *ent*-kaurane diterpenoids, which are one of the most characteristic chemical markers of this genus. *Jungermannia* species are morphologically and chemically interesting because they are generally polymorphic and their chemical constituents depend on the location of the collection site (40). Some other liverwort genera, such as *Apometzgeria*, *Bazzania*, *Cuspidatula*, *Frullania*, *Herbertus*, *Jackiella*, *Jamesoniella*, *Lepidolaena*, and *Plagiochila* species, produce kaurane diterpenoids.

Isophyllocladene (1132) was detected in *Bazzania japonica* (485). This is the second example of the presence of a kaurane in the genus *Bazzania* (40). The hydrocarbon *ent*-16-karene (1133), which might be a precursor of more highly oxygenated kaurane derivatives, is distributed widely both in higher plants and liverworts. Previously, compound 1133 was found in nine liverwort species. It has been detected in five additional liverworts, as shown in Table 4.3.

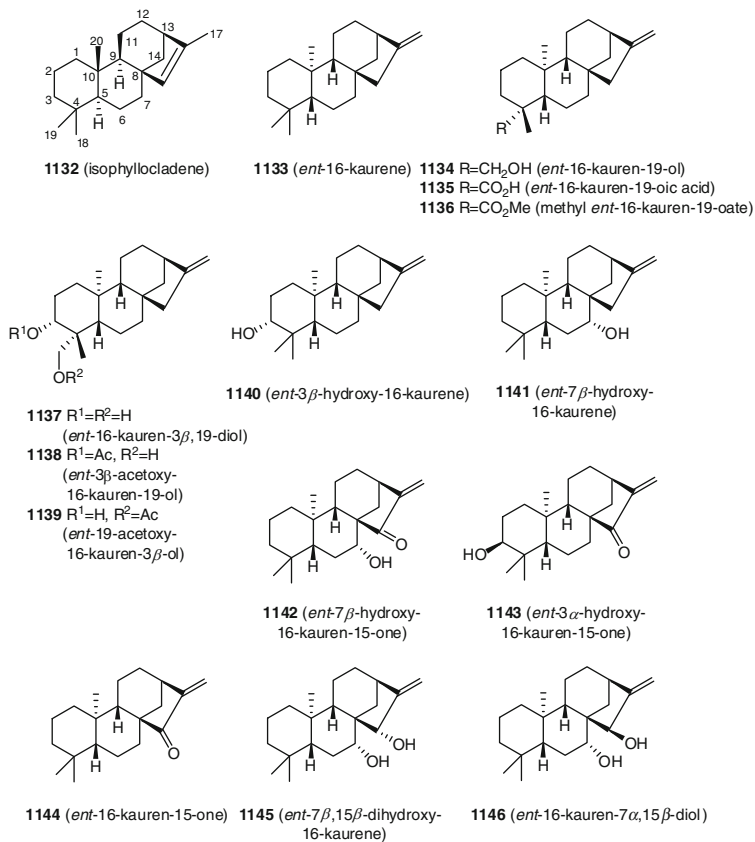
The New Zealand *Jamesoniella kirkii* elaborates the three known kauranes *ent*-16-karene-19-ol (1134), *ent*-16-karene-19-oic acid (1135), and methyl *ent*-16-karene-19-oate (1136). While the Japanese and European *Jamesoniella autumnalis* produces potent bitter clerodanes, *J. kirkii* is not bitter and no clerodanes were isolated from this species (84, 612).

Fractionation of the ether extract of *J. tasmanica* led to the isolation of the two new *ent*-karenes, *ent*-3 β -acetoxy-16-karene-19-ol (1138) and *ent*-19-acetoxy-16-karene-3 β -ol (1139), together with the known *ent*-16-karene-19-ol (1134) and *ent*-16-karene-3 β ,19-diol (1137). The positioning of a tertiary hydroxy group at C-14 was confirmed by the ^1H - ^{13}C correlation of H-20 with C-14 in the HMBC spectrum. Reduction of 1138 with LiAlH_4 gave a diol, for which the spectroscopic data and specific optical rotation value were identical to those of the known 1137 (89). Compound 1139 was also reduced by the same reagent as described above to yield a diol, which was also identical with 1137 (72, 872).

Herbertus alpinus elaborates *ent*-3 β -hydroxy-16-karene (1140) (558), which has also been found in the bark of the higher plant *Phyllanthus flexuosus* (805).

Further fractionation of the ether extract of the Malaysian *Jungermannia truncata* led to the isolation of the nine new *ent*-kaurane diterpenoids 1141–1143, 1145–1147, and 1149–1152, together with the known *ent*-16-karene-15-one (1144), *ent*-15 α -hydroxy-16-karene (1148), and *ent*-11 α -hydroxy-16-karene-15-one (1158). The latter compound has been isolated from this same liverwort collected in Japan, together with (16*R*)-*ent*-11 α -hydroxykauran-15-one (1155) (40). The newly isolated compounds mentioned above proved to be very similar to those of the known kauranes 1144, 1148, and 1158, and their structures were characterized as *ent*-7 β -hydroxy-16-karene (1141), *ent*-7 β -hydroxy-16-karene-15-one (1142), *ent*-3 α -hydroxy-16-karene-15-one (1143), *ent*-7 β ,

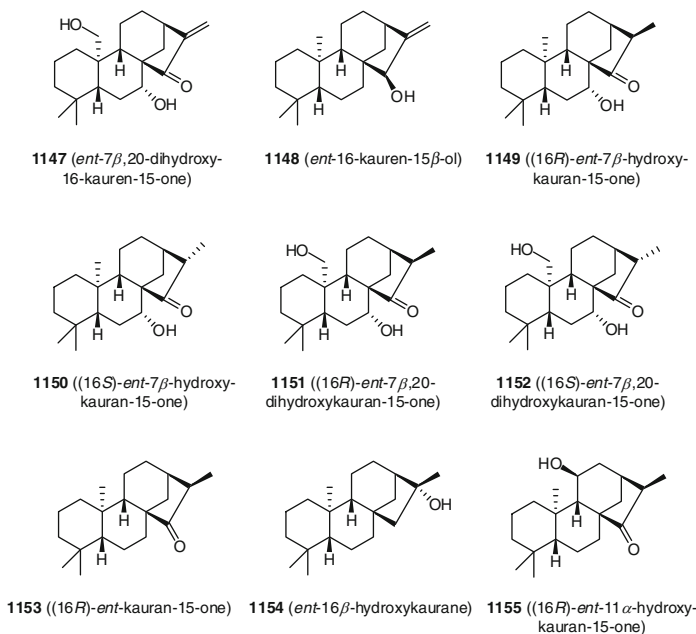
15 β -dihydroxy-16-kaurene (**1145**), *ent*-7 β ,15 α -dihydroxy-16-kaurene (**1146**), *ent*-7 β ,20-hydroxy-16-kauren-15-one (**1147**), (16*R*)-*ent*-7 β -hydroxykauran-15-one (**1149**), (16*S*)-*ent*-7 β -hydroxykauran-15-one (**1150**), (16*R*)-*ent*-7 β ,20-dihydroxykauran-15-one (**1151**), and (16*S*)-*ent*-7 β ,20-dihydroxykauran-15-one (**1152**), by analysis of their 2D-NMR data and by comparison with literature values for known kauranes and kaurenes (*136*). The 3 α -hydroxy isomer of **1143** has also been identified among the constituents of *Jungermannia vulcanicola* (*40*).



Kaurane-type diterpenoids found in the Marchantiophyta

Jungermannia truncata collected in a different location (Taiwan) gave the four kauranoids *ent*-16-kauren-15-one (**1144**), *ent*-16-kauren-15 α -ol (**1148**), *ent*-11 α -hydroxy-16-kauren-15-one (**1158**), and the new *ent*-14 α -hydroxy-16-kauren-15-one (**1163**), with the structure of the latter established by comparison of its spectroscopic data with those of other kaurenes found in the same species (*477*). Compounds **1144**, **1148**, and **1158**, have been found in the same Malaysian

specimen of *J. truncata*, as mentioned above. *Plagiochila pulcherrima* also produces *ent*-16-kauren-7 α ,15 β -diol (**1146**), *ent*-16-kauren-15 β -ol (**1148**), and *ent*-16 β -hydroxykaurane (**1154**) (477). Compound **1154** was also isolated from the liverworts, *Frullanoides densifolia* (40) and the Ecuadorian *Anastrophyllum auritum* (976). It is not common for *Anastrophyllum* and *Plagiochila* species to produce diterpenoids in the *ent*-kaurane series.



Kaurane-type diterpenoids found in the Marchantiophyta

The Taiwanese *Jungermannia truncata* was fractionated in the usual manner to afford two new *ent*-kauranes, for which the structures were determined as *ent*-(16*S*)-kauran-3,15-dione (**1191**) and *ent*-16-kauren-3,15-dione (**1192**), by analysis of their 2D-NMR spectroscopic data (477). Compounds **1191** and **1192** occurred together with the known *ent*-3 α -hydroxy-16-kauren-15-one (**1143**) and *ent*-16-kauren-15-one (**1144**), which were isolated from the Malaysian *J. truncata* (136) and *Jungermannia vulcanicola* (40).

Nagashima and associates reinvestigated the secondary metabolites of the Japanese *Jungermannia truncata* and isolated the five new *ent*-kauranes, *ent*-16,17-epoxykauran-15-one (**1198**), *ent*-14 α ,15 α -dihydroxykaurene (**1199**), *ent*-20-acetoxy-11 α -hydroxy-16-kauren-15-one (**1200**), *ent*-11 α -acetoxy-7 β ,14 α -dihydroxy-16-kauren-15-one (**1201**), and (16*R*)-*ent*-3 α -hydroxykauran-15-one (**1202**). These occurred together with the twelve known *ent*-kauranes **1143**, **1144**, **1148**, **1149**, **1153**, **1155**, **1157**, **1158**, **1160**, **1163** (40, 136, 477), rostronol F (**1164**), and 16,17-dihydrorastronol F (**1165**) (626), which have been obtained from *Jungermannia infusca*, along with the additional *ent*-kauranes **1144**, **1148**, and



Fig. 4.17 *Jungermannia exsertifolia*. (Permission for the use of this figure has been obtained from Mr. Masana Izawa, Saitama, Japan)

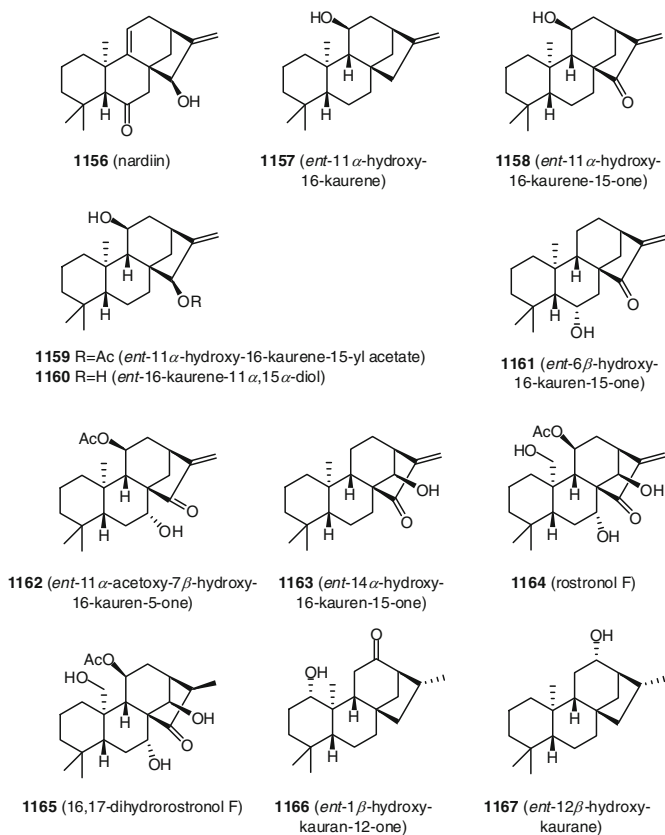
1158) (599). The structures of the newly isolated *ent*-kauranes were characterized from their 2D-NMR spectra and comparison of such data with those of known *ent*-kauranes (601). *Jackiella javanica* produces from the *ent*-kaurene series *ent*-16-kauren-15-one (**1144**) (608), *ent*-16-kauren-15 β -ol (**1148**), and *ent*-11 α -hydroxykauren-15-one (**1158**) (587).

Asakawa and associates derived the presence of the kauranes **1166** and **1167** in *Paraschistochila pinnatifolia* (72). The ethanol extract of the New Zealand *P. pinnatifolia* was purified by Sephadex and CC to afford *ent*-1 α -hydroxykauran-12-one (**1166**). The kaurane skeleton was proposed on the basis of the COSY, HMQC, and HMBC NMR data. Positioning of a hydroxy group and a carbonyl group in **1166** was supported by comparison of the NMR data of this compound with those of 1 β -hydroxymanolyl oxide and kauran-2,12-dione. The absolute configuration (16*R*) was confirmed by the identity of the coupling constant between H-13 and H-16 with that calculated from conformational searching using MacroModel software and the MM2 force field. The absolute configuration of **1166** was established by a positive Cotton effect at 295 nm (483). The second compound obtained (**1167**) was shown to be *ent*-12 β -hydroxykaurane (84).

The ether extract of the French *Jungermannia exsertifolia* subsp. *cordifolia* (Fig. 4.17) was fractionated to give the two new 6,7-*seco-ent*-kaurenes, secoexsertifolins A (**1176**) and B (**1177**), the bis-*ent*-kaurane, exsertifolin A (**1168**), and the seven new *ent*-kauranes, exsertifolins B (**1169**), C (**1170**), D (**1171**), E (**1172**), F (**1173**) G (**1174**), and H (**1175**), along with the seven known *ent*-kauranes, *ent*-11 α -hydroxy-16-kauren-15-one (**1158**), *ent*-11 α -hydroxy-16-kauren-15-yl acetate (**1159**), (16*R*)-*ent*-11 α -hydroxykauran-15-one (**1155**), *ent*-16-kauren-11 α ,15 α -diol (**1160**), *ent*-16-kauren-15 α -ol (**1148**), *ent*-16-kauren-15-one (**1144**), and nardiin (**1156**) (586). Of these, the latter compound has been obtained from *Nardia scalaris* (39, 40). The spectroscopic data showed all of the newly isolated

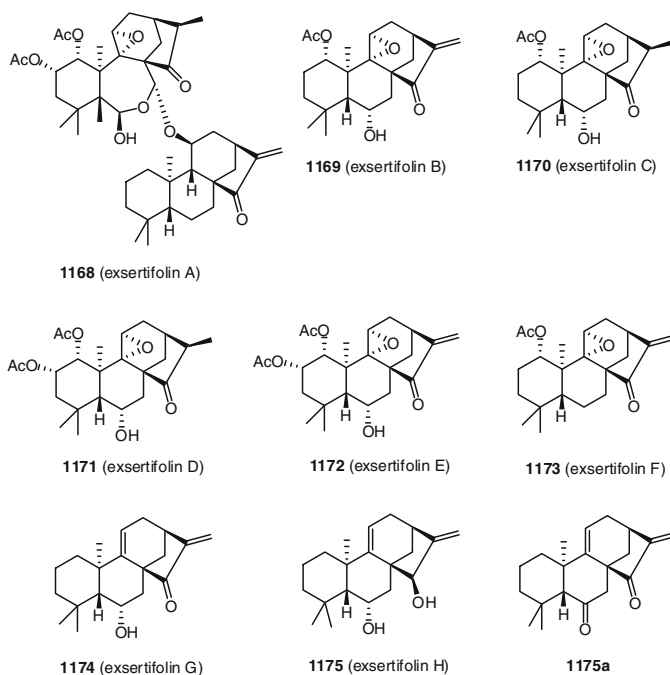
compounds to be representative of the kaurane and *seco*-kaurane series. The structures of secoexertifolins A (**1176**) and B (**1177**) were determined as 6,7-*seco*-kaurenes by a combination of X-ray crystallographic analysis of **1176** and chemical reaction on **1177**. Thus, hydrogenation of **1177** gave a dihydro derivative, for which the spectroscopic data were identical with those of **1176**. The NMR spectra of exertifolin A (**1168**) were similar to those of **1176** and *ent*-11 α -hydroxy-16-kauren-15-one (**1158**), isolated from the same species. The combination of NMR spectra and the molecular formula (C₄₄H₆₂O₁₀) showed that **1168** is a kaurene dimer. Conclusive evidence of the stereostructure of **1168** was provided by X-ray crystallographic analysis. Exsertifolins B (**1169**) and C (**1170**) were proven to be 1-acetoxy-6-hydroxy-C-11/C-12-epoxy-15-kauranone diterpenoids by a combination of X-ray crystallographic analysis of **1170** and chemical reaction on **1169**. Hydrogenation of **1169** gave a sole dihydro derivative with spectroscopic data identical with those of **1170**. The structures of exertifolins D (**1171**) and E (**1172**) were also characterized as *ent*-1 β ,2 β -diacetoxy-6 β -hydroxy-9 β ,11 β -epoxy-15-kauranone and *ent*-1 β ,2 β -diacetoxy-6 β -hydroxy-9 β ,11 β -epoxy-15-kaurenone by a combination of X-ray crystallographic analysis of **1172** and chemical reaction on **1172**. Again hydrogenation was used, and **1172** gave a sole dihydro derivative with spectroscopic data identical with those of **1171**. The structures of exertifolins F (**1173**) and G (**1174**) were assigned as dihydroxy derivatives of **1169** from their 2D-NMR data and by chemical correlation. Oxidation of **1174** gave a diketone derivative with spectroscopic data identical with those of nardiin (**1156**), co-occurring in the same species. Thus, structures **1173** and **1174** were established as *ent*-1 β -acetoxy-9 β ,11 β -epoxy-16-kauren-5-one and *ent*-6 β -hydroxykaura-9-(11),16-dien-5-one. The structure of exertifolin H (**1175**) was proposed as *ent*-kaur-9(11),16-dien-6 β ,15 α -diol from the interpretation of its 2D-NMR spectra and comparison with the analogous data of **1174**, and by chemical correlation with **1174**, **1175**, and **1175a**. Oxidation of **1175** with pyridinium dichromate gave the diketone **1175a**, for which the spectroscopic data were identical to those of **1175a** obtained from **1174**. The absolute configuration of all of the isolated kauranes was confirmed by Cotton effects of **1174** and **1175a** as well as from the co-occurrence of *ent*-kaurane series in the same species (**586**). English and Swiss samples of *J. exertifolia* subsp. *cordifolia* were found to produce trachylobane diterpenoids (**40**, **717**) (see Sect. 4.3.14).

The ethanol extract of the New Zealand liverwort *Lepidolaena taylorii* showed potent cytotoxicity against P388 leukemic cells. Bioactivity-directed fractionation led to three cytotoxic kauranes, of which one was identical with rabdoubrosanin (= *ent*-8,9-*seco*-7-hydroxykaura-8(14),16-dien-9,15-dione) (**1178**), isolated earlier from the higher plant, *Rhabdosia umbrosa* (**801**). The other compounds were 16,17-dihydorrabdoubrosanin (**1179**) and 8,14-epoxyrabdoubrosanin (**1180**). Compound **1179** was assigned as the C-16/C-17 dihydro derivative of **1178** from its NMR data. Conformational searching and molecular mechanics minimizations were used to predict the most stable configuration at C-16 for **1179**. The coupling constant of 7 Hz for H-16 to H-13 best matched the (16*R*) configuration. Epoxidation of **1178** afforded **1180**, indicating the structure of the latter compound to be 8,14-epoxyrabdoubrosanin (**652**).



Kaurane-type diterpenoids found in the Marchantiophyta

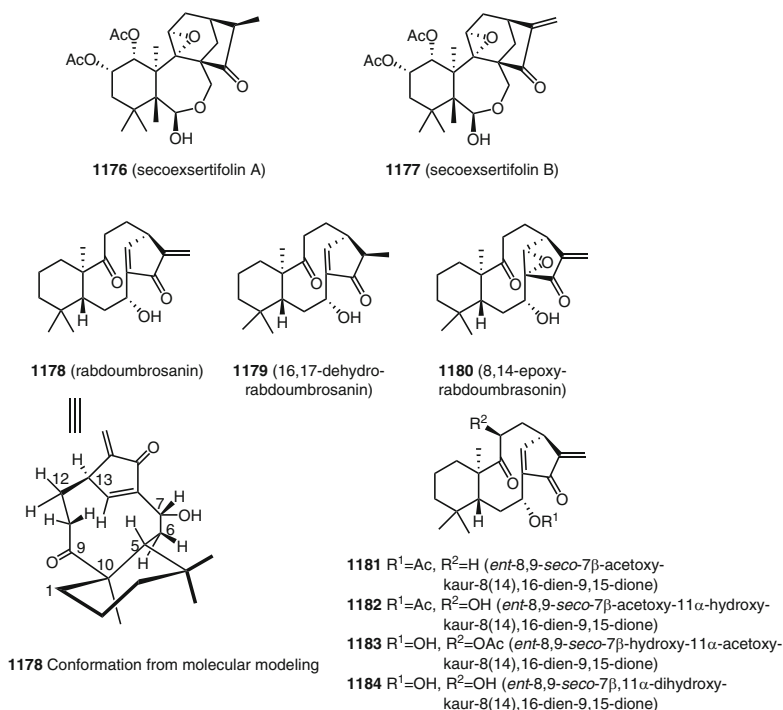
Further fractionation of the chloroform extract of the New Zealand *Lepidolaena taylorii* on a C₁₈ column resulted in the isolation of the four new additional 8,9-secokaurane diterpenoids, *ent*-8,9-*seco*-7 β -acetoxykaura-8(14),16-dien-9,15-dione (**1181**), *ent*-8,9-*seco*-7 β -acetoxy-11 α -hydroxykaura-8(14),16-dien-9,15-dione (**1182**), *ent*-8,9-*seco*-7 β -hydroxy-11 β -acetoxykaura-8(14),16-dien-9,15-dione (**1183**), and *ent*-8,9-*seco*-7 β ,11 α -dihydroxykaura-8(14),16-dien-9,15-dione (**1184**), along with the known 8,9-secokaurane, rabdoubrosanin (**1178**), its dihydro and epoxy derivatives **1179** and **1180**, and 3 β -acetoxy-7 α ,9 β ,14 β -trihydroxykaur-16-en-15-one, shikoccidin (**1187**) (654). Furthermore, three new *ent*-kaur-16-en-15-ones, *ent*-7 β , 14 α -dihydroxykaur-16-en-15-one (**1185**), *ent*-7 β -acetoxy-14 α -hydroxykaur-16-en-15-one (**1186**), and *ent*-14 α -hydroxy-16-kauran-15-one (**1163**) were isolated, together with the known *ent*-7 β -hydroxykaur-16-en-15-one (**1142**) (136) and *ent*-kaur-16-en-15-one (**1144**) (40, 586). The yield of the purified *ent*-8,9-secokaurane (**1178**) was about 0.5 mg/g of the dried liverwort (654). Another New Zealand endemic liverwort, *Lepidolaena palpebrifolia*, also elaborates the 8,9-secokauranes **1178** and **1180** (654).



Kaurane-type diterpenoids found in the Marchantiophyta

Molecular mechanics calculations (MM2 force field) and the Monte Carlo method were used to predict the solution conformation of **1178**. The two most stable conformers, predicted to be >98% of the population in the gas phase, differed only in the orientation of the C-7 hydroxy group. They possess the same skeletal conformation as found in the crystal structure of another 8,9-*seco*-kaurane, shikoccin monoacetate, with the six-membered ring in a chair conformation and the C-9 carbonyl oxygen *syn* with the C-10 methyl group, as shown in **1178**.

The spectroscopic data of **1181** were found to be very similar to those of **1178**. Acetylation of **1178** gave a monoacetate with spectroscopic data identical with those of **1181**. The structure of **1182** was also based on the characteristic fragment ions (m/z 123 and 138) in the mass spectrum due to the presence of a mono-oxygenated six-membered ring. The full structure of **1182** was established using a combination of its 2D-NMR data. The structures of compounds **1183** and **1184** were determined by comparison of NMR spectroscopic data with those of the aforementioned 8,9-*seco*-kauranes. The structure of the newly isolated kaurene-15-one **1185** was proved by comparison of its NMR data with those of the co-occurring *ent*-kaurene-15-one (**1176**), which was isolated from several other liverwort species (40, 586). Compound **1186** was readily ascribed as the 7-acetate of **1185** by comparison of NMR spectra. Compound **1163** was postulated to be *ent*-14 α -hydroxykaur-16-en-15-one, by comparison of its ^{13}C NMR spectrum with those of **1176**, **1185**, and **1186** (477, 652, 654).

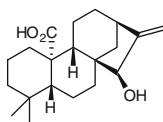
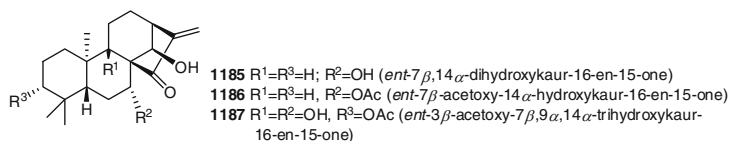
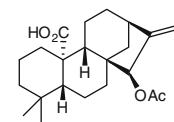
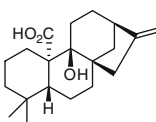
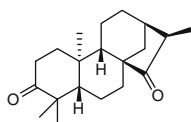
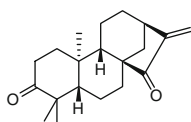
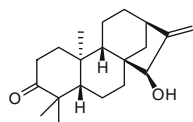
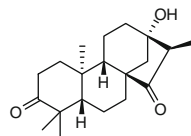
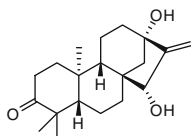
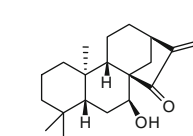
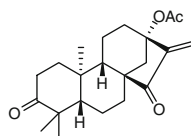
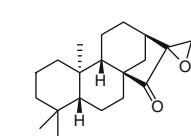
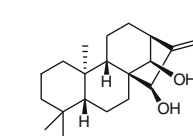
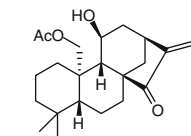
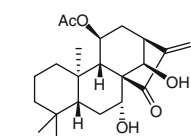
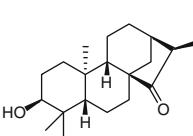


Kaurane-type diterpenoids found in the Marchantiophyta

The Japanese *Jungmannia rotundata* elaborates three unusual *ent*-kauranes, named rotundeic acids A-C (**1188**–**1190**). The complete structures of **1188** and **1189** including the positioning of a carboxylic acid unit at C-10 in each case were proven by a combination of chemical reaction and the detailed analysis of COSY, HMBC, and NOESY experiments of **1189**, which was obtained from **1188** by reduction. The C-10 α stereochemistry of a carboxylic acid group was confirmed by the difficulty of obtaining the C-10 alcohol from **1188** under vigorous conditions. A negative *Cotton* effect of a kaur-16-en-15-one-20-oic acid prepared from **1188** by PDC oxidation showed that compounds **1188** and **1189** are representative of the *ent*-kaurene series. Thus, the absolute configurations of **1188** and **1189** were determined as *ent*-15 α -hydroxykaur-16-en-20-oic acid (**1188**) and *ent*-15 α -acetoxykaur-16-en-20-oic acid (**1189**). The position and stereochemistry of the hydroxy group of **1190** was proven to be C-9 β *axial* by COSY and HMBC experiments, and induction of ^1H NMR solvent shifts in pyridine- d_5 . The final structure of **1190** was established as *ent*-9 α -hydroxykaur-16-en-20-oic acid. This was the first isolation of *ent*-kauranes with a carboxylic acid at C-10 from either the bryophytes or the higher plants (**588**).

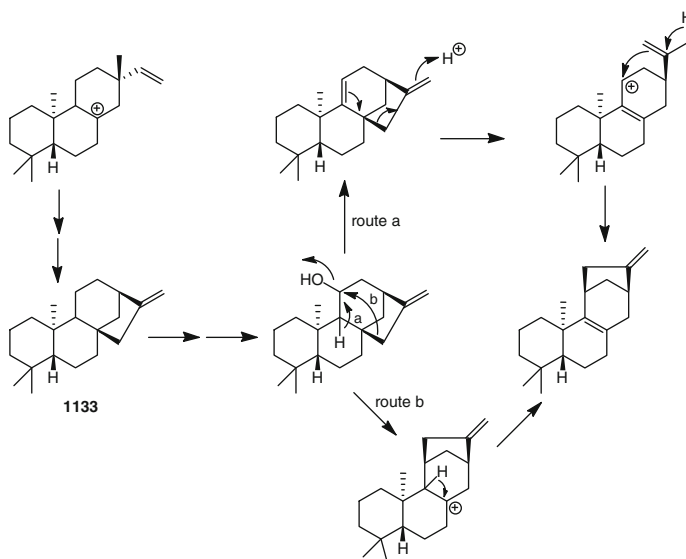
A suspension culture of *Jungermannia subulata* was studied chemically and three new *ent*-kaurenes, *ent*-kaur-16-ene-3,15-dione (**1192**), 15 β -hydroxy-*ent*-kaur-16-en-3-one (**1193**), and 3 β -hydroxy-*ent*-(16*S*)-kauran-15-one (**1202**) were isolated together with three known kaurenes. The intact *J. subulata* also contained two new *ent*-kaurenes along with three known analogues (629). Conclusive evidence of the structure of **1193** as 15 β -hydroxy-*ent*-kaur-16-en-3-one was settled by X-ray crystallographic analysis, and its absolute configuration was determined by the formation of **1192** from **1193** by Jones oxidation. Compounds **1194** and **1195** were established as 13 α -hydroxykaurane-3,15-dione and 13 α ,15 α -dihydroxykauran-3-one, on the basis of their HMBC and NOESY spectra. Their absolute configurations were suggested from their co-occurrence with other compounds from the same plant in the *ent*-kaurane series.

The methanol extract of the field-collected *J. subulata* contained *ent*-kaurene (**1192**) together with **1144**, **1158**, **1196**, and **1197**, of which **1144** and **1158** are the previously known compounds *ent*-kaur-16-en-15-one and 11 β -hydroxy-*ent*-kaur-16-en-15-one (40). The relative and absolute stereostructures of both **1196** and **1197** were established from the HMBC and NOESY NMR spectra and/or X-ray crystallographic analysis and their co-occurrence with related *ent*-kaurenes (629). Tazaki and colleagues isolated *ent*-kaurenone (**1191**) from a cell culture of *J. subulata* as well as from a field specimen, along with *ent*-kaur-16-ene (**1133**), 15 β -hydroxy-*ent*-kaur-16-ene (**1148**), and *ent*-kaur-16-en-15-one (**1144**) (822). The relative stereochemistry of **1191** was elucidated by X-ray crystallographic analysis. The absolute configurations of compounds **1191** and **1192** have been determined by Nozaki and associates (629). The absolute configuration of **1191** was based on the formation of this compound from **1202** by Jones oxidation. The absolute structure of **1192** was also established by X-ray crystallographic analysis and the formation of **1191** from **1192** by hydrogenation. The abundance of *ent*-kauranes from cultured cells of *J. subulata* was estimated to be almost the same level as when collected in the field. On the other hand, Nozaki and colleagues reported that the kaurenes found in the intact plant are different from those in suspension culture of *J. subulata* in their oxidation-reduction levels (629). The same authors also suggested that such differences of the oxidation and reduction profiles of the kaurene skeleton might be catalyzed by cytochrome 450 oxido-reductases, monooxygenases, and NADH/NADPH-dependent reductases, which are different in the cell culture and intact plant and are affected by the culturing condition or the growth environment (629).

**1188** (rotundeic acid A)**1189** (rotundeic acid B)**1190** (rotundeic acid C)**1191** (*ent*-kaurane-3,15-dione)**1192** (*ent*-kaur-16-en-3,15-dione)**1193** (15 β -hydroxy-*ent*-kaur-16-en-3-one)**1194** (13 α -hydroxy-*ent*-kauran-3,15-dione)**1195** (13 α ,15 α -dihydroxy-*ent*-kaur-16-en-3-one)**1196** (7 β -hydroxy-*ent*-kaur-16-en-15-one)**1197** (13 α -acetoxy-*ent*-kaur-16-en-3,15-dione)**1198** (*ent*-16,17-epoxy-kauran-15-one)**1199** (*ent*-14 α ,15 α -dihydroxy-16-kaurene)**1200** (*ent*-20-acetoxy-11 α -16-kauran-15-one)**1201** (*ent*-11 α -acetoxy-7 β ,14 α -dihydroxy-16-kauran-15-one)**1202** ((16*R*)-*ent*-3 α -hydroxy-kauran-15-one)

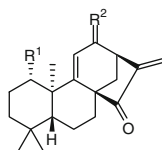
Kaurane-type diterpenoids found in the Marchantiophyta

The ether extract of an unidentified New Zealand *Jungermannia* species was separated by column chromatography to afford the two new *ent*-kauranes **1203** and **1204**, and a new rearranged kaurane, named jungermannenone A (**1205**), together with *ent*-11 α -hydroxy-16-kauran-15-one (**1158**), and (16*R*)-*ent*-11 α -hydroxykauran-15-one (**1155**). A combination of 2D-NMR data analysis and a *Cotton* effect determination was used to confirm the absolute structure of **1203** as *ent*-1 β -hydroxy-9(11),16-kauradien-15-one. The structures of both **1204** and

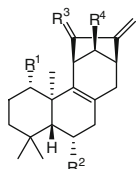


Scheme 4.40 Formation of rearranged kaurane-type diterpenoids

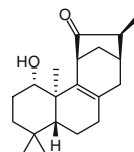
jungermannenone A (**1205**) were deduced as *ent*-9(11),16-kauradiene-12,15-dione and its C-11/C-13 cyclic kaurane derivative, from their respective 2D-NMR data (602). Further fractionation of the same ether extract led to the isolation of the four rearranged kauranes, **1206–1209**, named jungermannenones B–E, the eight *ent*-kauranes, **1210–1218**, and the four known kauranes, **1144** and **1160–1162**. The absolute configuration of jungermannenone A (**1205**), previously isolated from the same liverwort, was established by a combination of its 2D-NMR data and the X-ray crystallographic analysis of the (–)-camphanic ester of a diol prepared from **1205** by reduction with LiAlH_4 (609, 610). The stereochemistry of **1216** was settled using its 2D-NMR data including the NOESY spectrum and from its X-ray crystallographic analysis. The absolute configurations of the other kauranes were determined by a combination of the interpretation of their 2D-NMR spectra and Cotton effect measurements, except for compounds **1212**, **1215**, and **1216**. Their absolute configurations were predicted to be the same as those found in the same species. The rearranged kaurenes might be formed from an *ent*-kaurene **1133** via an *ent*-9(11)-kaurene-type intermediate, followed by cleavage of the five-membered ring and recyclization (route a) or from the elimination of the hydroxy group at C-11 and 1,3-rearrangement (route b), as shown in Scheme 4.40 (609).



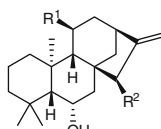
1203 $R^1=OH$, $R^2=H$, H (*ent*-1 β -hydroxy-9(11),16-kauradien-15-one)
1204 $R^1=H$, $R^2=O$ (*ent*-9(11),16-kauradien-12,15-dione)



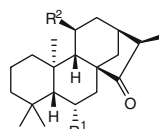
1205 $R^1=OH$, $R^2=R^4=H$, $R^3=O$ (jungermannenone A)
1206 $R^1=R^2=R^4=H$, $R^3=O$ (jungermannenone B)
1207 $R^1=R^2=H$, $R^3=O$, $R^4=OH$ (jungermannenone C)
1208 $R^1=R^4=OH$, $R^2=H$, $R^3=O$ (jungermannenone D)
1209 $R^1=R^4=H$, $R^2=OH$, $R^3=O$ (jungermannenone E)



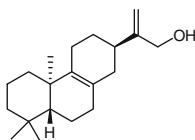
1210 (16 α ,17-dihydro-jungermannenone A)



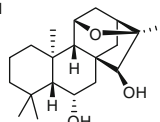
1211 $R^1=H$, $R^2=OH$ (*ent*-16-kauradien-6 β ,15 α -diol)
1212 $R^1=R^2=OH$ (*ent*-16-kauradien-6 β ,11 α ,15 α -triol)



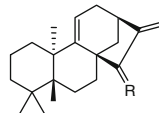
1213 $R^1=OH$, $R^2=H$ ((16*R*)-*ent*-6 β -hydroxykaur-15-one)
1214 $R^1=R^2=OH$ ((16*R*)-*ent*-6 β ,11 α -dihydroxykaur-15-one)



1215 (8,15-*seco*-8,16-*ent*-kauradien-15-ol)



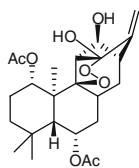
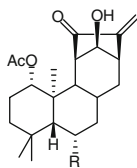
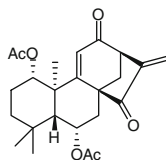
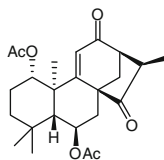
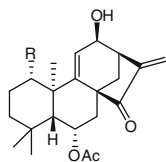
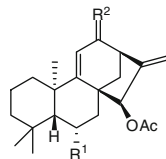
1216 (*ent*-11 α ,15 α -epoxy-kauran-6 β ,15 α -diol)



1217 $R=\beta OH$, αH (*ent*-9(11),16-kauradien-15 α -ol)
1218 $R=O$ (*ent*-9(11),16-kauradien-15-one)

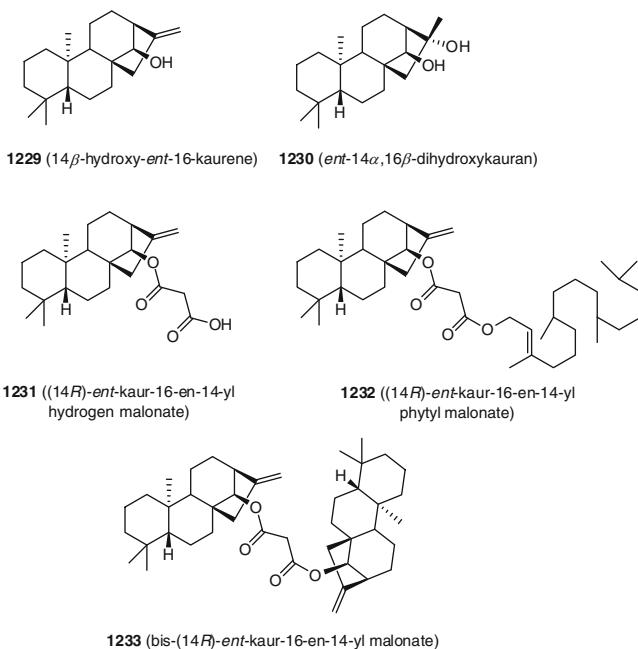
Kaurane-type diterpenoids found in the Marchantiophyta

The ten new *ent*-kauranes **1219–1228** were isolated from the aquatically habituated Chinese *Jungmannia atrobrunnea* grown at 1610 m in altitude. The relative stereostructure possessing a C-9 to C-15 peroxy bridge was based on X-ray crystallographic analysis (668). The absolute configurations of all of these kauranes were established by their CD spectra (609).

**1219** (jungermatrobrunin A)**1220** R=OAc (1 α ,6 α -diacetoxyjungermannone C)**1221** R=OH (1 α -acetoxy-6 α -hydroxyjungermannone C)**1222** (1 α ,6 α -diacetoxy-*ent*-9(11),16-kauradien-12,15-dione)**1223** ((16*R*)-1 α ,6 α -diacetoxy-*ent*-9(11)-kauren-12,15-dione)**1224** R=OAc (1 α ,6 α -diacetoxy-12 β -hydroxy-*ent*-9(11),16-kauradien-15-one)**1225** R=OH (6 α -acetoxy-1 α ,12 β -dihydroxy-*ent*-9(11),16-kauradien-15-one)**1226** R¹=OH, R²=H, H (15 β -acetoxy-6 α -hydroxy-*ent*-9(11),16-kauradiene)**1227** R¹=OAc, R²=H, H (6 α ,15 β -diacetoxy-*ent*-9(11),16-kauradiene)**1228** R¹=OAc, R²=O (6 α ,15 β -diacetoxy-*ent*-9(11),16-kauradien-12-one)

Kaurane-type diterpenoids found in the Marchantiophyta

An ether extract of *Nardia subclavata* was reinvestigated chemically to isolate the three known kaurene malonate esters, (14*R*)-*ent*-kaur-16-en-14-yl phytyl malonate (**1232**), bis-(14*R*)-*ent*-kaur-16-en-14-yl malonate (**1233**), and (14*R*)-*ent*-kaur-16-en-14-yl hydrogen malonate (**1231**), along with *ent*-14 α -hydroxykaur-16-ene (**1229**) and *ent*-14 α ,16 β -dihydroxykaurane (**1230**), which were isolated from this liverwort for the first time ([84](#)).



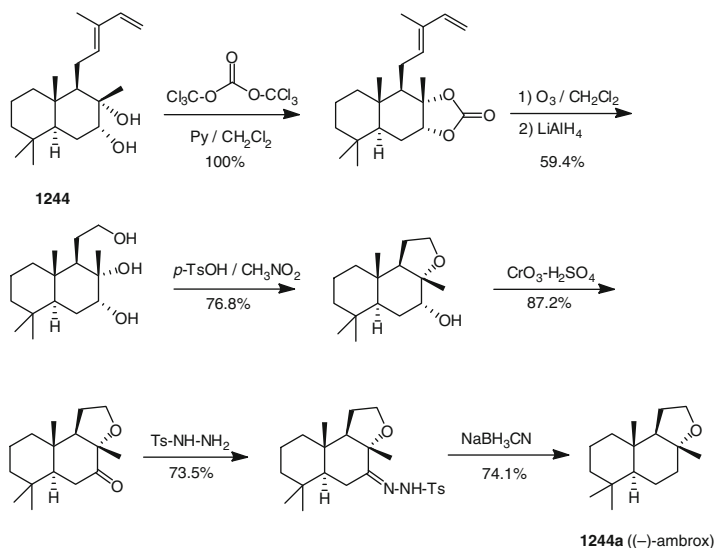
Kaurane-type diterpenoids found in the Marchantiophyta

4.3.8 Labdanes

The diterpenoids present in liverworts of the genus *Jungermannia* are quite interesting biogenetically. *J. hattoriana* produces compounds of both the labdane-type, with a 10 β -methyl group, and (–)-pimarane diterpenoids with a 10 α -methyl group. *J. infusca* elaborates both normal labdane-type and *ent*-clerodane diterpenoids (592).

The ether extract of the New Zealand *Herbertus alpinus* was fractionated by CC to give labda-8(17),(12*E*),14-triene (1234), labda-8(17),(12*E*),14-trien-6 α -ol (1235), and *ent*-3 β -hydroxy-8(17),(12*E*),14-labdatriene (1236) (72, 558, 616). The structure of compound 1234 was deduced by comparison of its spectroscopic data with values of the synthetic labda-8(17),(12*Z*),14-triene. The absolute configuration of 1234 was determined by the modified Mosher method. The other two structures were based on 2D-NMR spectroscopic data analysis.

Nagashima and associates (590) reported that an ether extract of the Japanese *Jungermannia hattoriana* contained the new (+)-labda-8(17),14-diene-(9*R**,13*S**)-diol (1237), along with (13*S*)-hydroxy-8,14-labdadiene (1240), which has been found in higher plants (107, 686), and 13-*epi*-sclareol (1243) (855). The stereostructures of 1237 and 1243 were determined unequivocally by X-ray crystallographic analysis. The labdanes 1240 and 1243 possess a 10 β -methyl and the pimaranes (Sect. 4.3.10.)



Scheme 4.41 Hemisynthesis of (–)-ambrox from labda-(12*E*),14-dien-7,8-diol

a 10 α -methyl group. *Jungermannia truncata* produces the same labdanes **1237** and **1243** (569). This is the first example of the isolation of diterpenoids with both the 10 β - and 10 α -methyl group in the same liverwort species (590).

A new 8,9-*seco*-labdane, named secoinfuscadione (**1238**), was obtained from the ether extract of *Jungermannia infusca* collected in Tochigi, Japan, together with labda-8(17),14-diene-(9*R**,13*S**)-diol (**1237**) (591). The structures of **1238** and infuscadiol (**1239**), isolated from the same species, were assigned by analysis of their 2D-NMR data (¹H-¹H COSY, ¹³C-¹H COSY HMQC, HMBC, NOESY). The latter compound might be formed by intramolecular aldol condensation of **1238** (595). Diterpenoids possessing the 8,9-*seco*-labdane- and rearranged labdane-type skeletons have been isolated from the higher plants, *Gyophamnum pinifolium* (Gochnatiinae) (978) and *Galeopsis angustifolia* (Labiatae) (650). These skeletons are rare in Nature and were reported from a liverwort source for the first time.

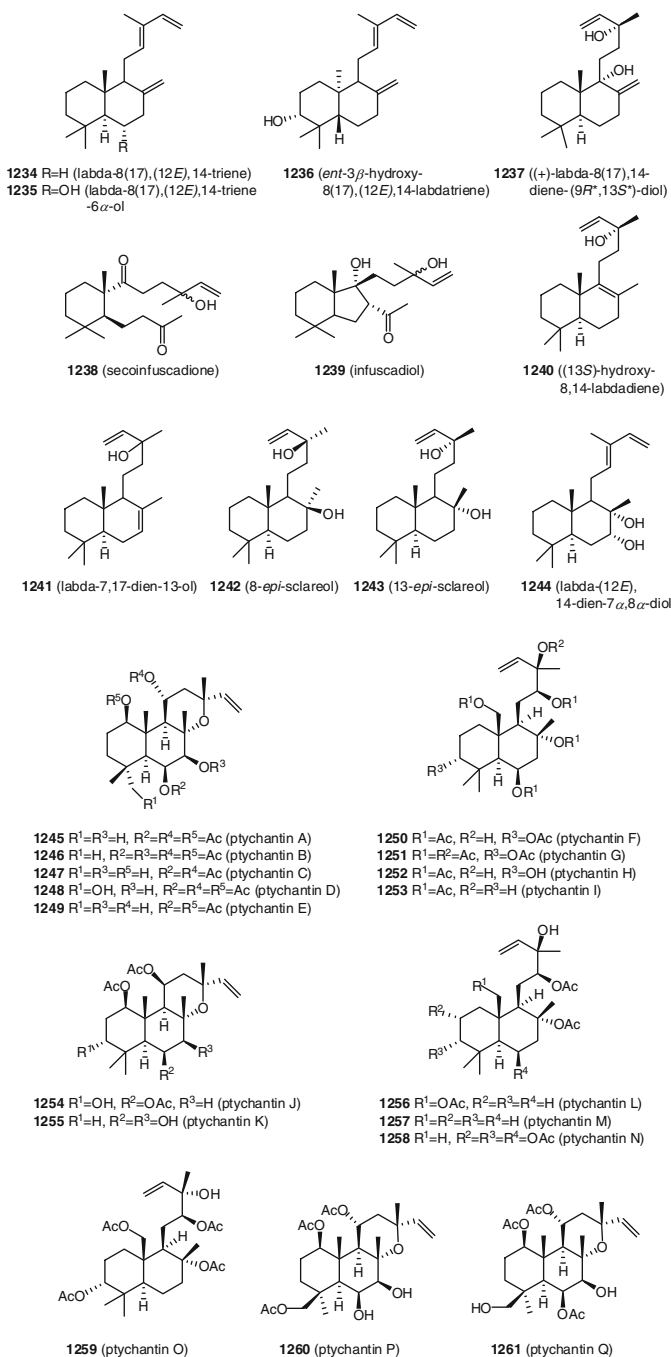
The ether extract of the Japanese *Porella perrottetiana* was purified to give labda-12,14-dien-7 α ,8 α -diol (**1244**), with its absolute stereostructure determined by a combination of 2D-NMR (HMBC and NOESY) methods and a negative (247 nm) and a positive (220 nm) Cotton effect observed for its 7-*p*-bromobenzoate derivative (318). Hashimoto and colleagues conducted the chemical conversion of **1244** to the animal perfume, (–)-ambrox (**1244a**), via six steps (Scheme 4.41) (318).

Ptychanthus striatus is an attractive liverwort that contains large amounts of the highly oxygenated labdane diterpenoids, ptychantins A-E (**1245**–**1249**) (40). Further fractionation of the ether extract of *P. striatus* led to the isolation of ptychantins F-I (**1250**–**1253**) (308). The structure of **1250** was deduced from its ¹H and ¹³C

NMR spectroscopic data and by chemical reaction. Dehydration of **1250** with POCl_3 and pyridine afforded a mixture of products with a double bond at C-12, C-13/C-13,C-16. Reduction of **1250** by LiAlH_4 gave a hexahydroxy derivative, which was converted to an acetonide with 2,2-dimethoxypropane and then to the C-12 aldehyde by oxidation with NaIO_4 . Conclusive evidence for the proposed structure was obtained by X-ray crystallographic analysis of **1250**. Acetylation of **1250** gave the natural product ptychantin G (**1251**). Acetylation and oxidation of **1252** gave **1250** and a 3-oxo derivative, indicating that **1252** is 3-deacetyl-ptychantin F. The structure of ptychantin I (**1253**) was established by X-ray crystallographic analysis. The absolute configurations of ptychantins F-I (**1250**–**1253**) were assigned from the negative *Cotton* effect at 317 nm of the 3-oxo derivative of **1242**, and on the basis of their co-occurrence in the same organism of origin as ptychantins A-E (**1245**–**1249**), for which the absolute configurations had been determined (**308**).

Further fractionation of the ethyl acetate extract of the Taiwanese *P. striatus* resulted in the isolation of ptychantins J-N (**1254**–**1258**) together with ptychantins G (**1251**) and I (**1253**) (**957**). The structures of the newly isolated compounds **1254**–**1258** were determined by a combination of the interpretation of their ^1H - and ^{13}C NMR spectroscopic data, and comparison with those of other ptychantin derivatives, with particular emphasis on the analysis of HMBC and NOESY experiments. In addition, manoyl oxide (**1288**), labda-7,14-dien-13-ol (**1241**), and 13-*epi*-sclareol (**1243**) were isolated or identified in the same species collected in different Taiwanese locations. Compounds **1288** and **1241** were isolated from the Taiwanese *Mylia nuda* (**40**). Compound **1243** was isolated in addition from the Japanese *Jungermannia hattoriana* (**590**) and *J. infusca* (**592**), as mentioned above.

Hashimoto and colleagues reinvestigated the methanol extract of *P. striatus* to obtain two new labdanes named ptychantins J (**1260**) and K (**1261**) (**325**). However, *Wu et al.* had already used these names for different ptychantins, as mentioned above (**957**). Furthermore, two years after *Hashimoto's* paper appeared, *Kawahara* and associates reported a new labdane, ptychantin O (**1259**), together with the known ptychantin G (**1251**) and ptychantin F (**1250**) (**399**). Thus, the names of ptychantin J and K as used by *Hashimoto* and colleagues (**325**) should be changed to ptychantins P (**1260**) and Q (**1261**). The structure of **1260** was established using a combination of its NMR data and by X-ray crystallographic analysis. Compound **1261** was partially hydrolyzed by potassium methanolate in methanol to give the 6,19-deacetyl derivative. Acetylation then gave the 1,19-diacetate, which was also obtained from compound **1260** by partial acetylation. Thus, the relative stereostructure of **1261** represents an epimer of ptychantin E (**1249**) at C-4. The absolute configurations of **1260** and **1261** were established in the manner following. The 6,7,19-trihydroxy derivative of **1261** was treated with 2,2-dimethoxypropane to give the 6,19-acetonide and 6,7-acetonide. Application of the *Mosher* method for the former acetonide led to the absolute stereochemistry as depicted in the structure (**325**). Ptychantin O (**1259**) was determined to be the 6-deacetoxy derivative of ptychantin F (**1250**) by comparison of its ^1H - and ^{13}C NMR data with those of ptychantin F (**1250**), with the use of COSY, HMQC, HMBC, and NOESY experiments. While the intact plant produces ptychantins A (**1245**) and B (**1246**), these compounds were not detected in the ethyl acetate extract of the cultured cells (**399**).

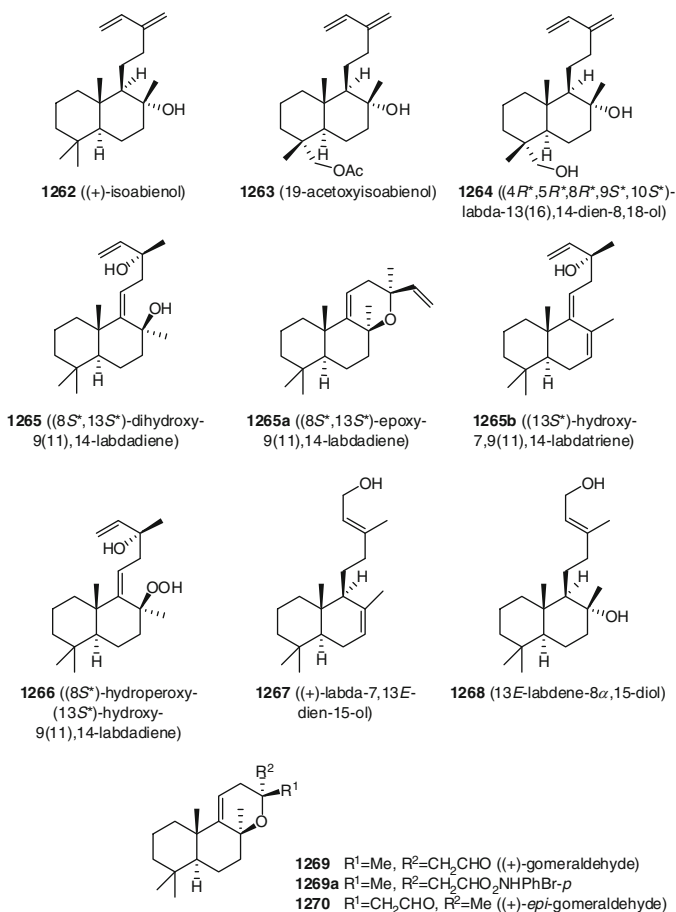


Labdane-type diterpenoids found in the Marchantiophyta

Two labdanes, 8,18-dihydroxyabda-13(16),14-diene (**1264**) and its acetate (**1263**), were isolated from the ether extract of the New Zealand *Plagiochila cricinalis* (635). Compound **1264** has been found in the higher plant, *Sideritis* species, and **1263** was reported as the acetylated product of **1264** (246). The absolute structures of both compounds still remain to be clarified.

Labdanes **1243**, **1262**, and **1268–1270** were obtained from the ether extract of *Jungermannia infusca*. The absolute configuration of gomerinaldehyde (**1269**) was confirmed by X-ray crystallographic analysis of a carbamate derivative **1269a** with that of its 13-epimer *epi*-gomerinaldehyde (**1270**) inferred as being the same. Compound **1262** is isoabienol, for which the absolute configuration was confirmed by the positive sign of its optical rotation and its co-occurrence with compounds **1269** and **1270** that possess the normal labdane structure. Chiroselective HPLC analysis of **1262** showed the presence of a tiny amount (0.3%) of its enantiomer (592).

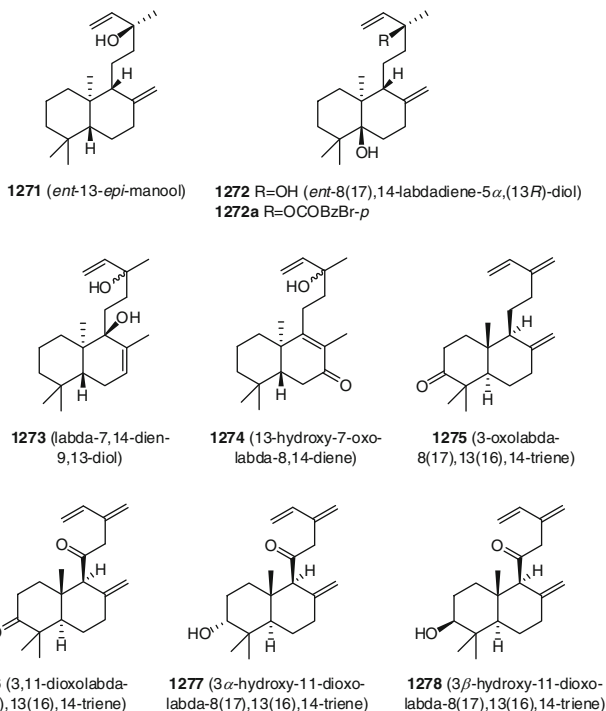
Reinvestigation of the chemical constituents of *J. infusca* led to the isolation of the two new labdanes, (8*S**,13*S**)-dihydroxy-9(11),14-labdadiene (**1265**) and (8*S**)-hydroperoxy-(13*S**)-hydroxy-9(11),14-labdadiene (**1266**) together with infuscadiol (**1239**), along with the two labdanes **1237** and **1238** (39, 595), as well as (13*S*)-hydroxy-8,14-labdadiene (**1240**) and 13-*epi*-sclareol (**1243**). The relative configurations of **1265** and **1266** were established by a combination of 2D-NMR analysis of **1265** and **1266**, X-ray crystallographic analysis of **1265**, and chemical correlation between **1265** and **1266**. Reduction of **1266** with LiAlH₄ gave a dihydroxyabdadiene with spectroscopic data identical to those of **1265**. When compound **1265** was allowed to stand overnight in CDCl₃, a dehydration reaction occurred to afford (13*S**)-hydroxy-7,9(11),14-labdatriene (**1265b**) and (8*S**,13*S**)-epoxy-9(11),14-labdadiene (**1265a**) (595).



Labdane-type diterpenoids found in the Marchantiophyta

Further investigation of the ether extract of *Marchantia paleacea* var. *diptera*, collected in a different location, led to the isolation of the same (+)-labda-7,(13*E*)-dien-15-ol (**1267**) (436) as found previously in this species (40).

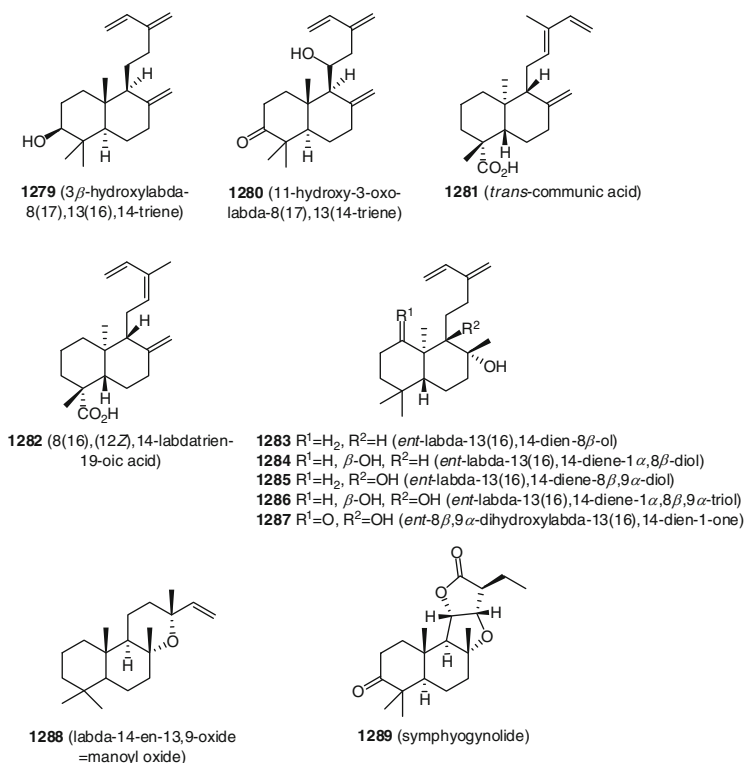
The ether extract of *Jungermannia vulcanicola* produced the new labdane, *ent*-8(17),14-labdadiene-5 α ,(13*R*)-diol (**1272**), and *ent*-13-*epi*-manool (**1271**) (632). The NMR data of **1272** were similar to those of **1271**, indicating that **1272** is a labdane derivative. The position and stereochemistry of an alcohol at C-5 was confirmed using its ^{13}C NMR and NOESY spectroscopic data. The absolute configuration was proven by the negative *Cotton* effect (258 nm) of the *p*-bromobenzoate (**1272a**) of **1272** (585).



Labdane-type diterpenoids found in the Marchantiophyta

The ethyl acetate extract of the Taiwanese *Jungermannia appressifolia* was purified by CC to give the two new labdanes, labda-7,14-diene-9,13-diol (**1273**) and 13-hydroxy-7-oxolabda-8,14-diene (**1274**), along with labda-8,14-dien-13-ol (**1240**). The absolute configurations of **1273** and **1274** were arrived at by 2D-NMR spectroscopic data analysis and the positive *Cotton* effect at 342 nm of **1274** (952).

The dichloromethane extract of the Chilean *J. colorata* was fractionated to give the six new labdanes, 3-oxolabda-8(17),13(16),14-triene (**1275**), 3,11-dioxolabda-8(17),13(16),14-triene (**1276**), 3 α -hydroxy-11-oxolabda-8(17),13(16),14-triene (**1277**), 3 β -hydroxy-11-oxolabda-8(17),13(16),14-triene (**1278**), 3 β -hydroxylabda-8(17),13(16),14-triene (**1279**), and 11-hydroxy-3-oxolabda-8(17),13(16),14-triene (**1280**) (340), for which their structures were based on ^1H - ^1H -COSY, HSQC, HMBC and NOESY experiments. The absolute configuration of **1275** was arrived at by a negative *Cotton* effect at 210 nm.



Labdane-type diterpenoids found in the Marchantiophyta

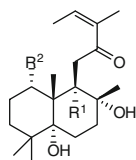
The labdane, *trans*-communic acid (= 8(16),12*E*,14-labdatrien-19-oic acid) (**1281**), was isolated from the ether extract of the North American *Porella navicularis* (143) and *Plagiochila ovalifolia* (84). The *n*-hexane extract of *Marchantia emarginata* subsp. *tosana* was fractionated over silica gel to give 8-(16),12*Z*,14-labdatrien-19-oic acid (**1282**), for which the structure was settled using HMQC, HMBC, and NOESY experiments (347). In turn, *trans*-communic acid (**1281**) has been isolated from *Jamesoniella autumnalis* (40).

Previously, five flavone *C*-glycosides have been found in the methanol extract of the very tiny liverwort, *Blepharostoma trichophyllum*. Fractionation of the dichloromethane extract of the *in vitro*-cultured *B. trichophyllum* resulted in the isolation of the five new *ent*-labdanes, **1283**–**1287**, for which their stereostructures were proven to be *ent*-labda-13(16),14-dien-8 α -ol (**1283**), *ent*-labda-13(16)-14-diene-1 β ,8 α -diol (**1284**), *ent*-labda-13(16),14-diene-8 α ,9 β -diol (**1285**), *ent*-labda-13(16),14-diene-1 β ,8 α ,9 β -triol (**1286**), and *ent*-8 α ,9 β -dihydroxy-labda-13(16),14-dien-1-one (**1287**), by 2D-NMR (¹H-¹H-COSY, HMQC, HMBC, and NOESY) methods. Their absolute configurations were established by a positive Cotton effect of **1287** at 310 nm (215).

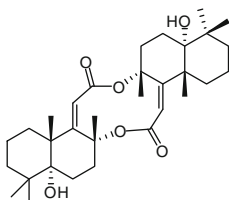
The ether extract of the Venezuelan *Symphyogyna brasiliensis* was purified by CC and preparative TLC to give a new labdane diterpene named symphygynolide

(**1289**), with its structure proven by considering its IR (1780 and 1700 cm^{-1} assignable to a lactone and a carbonyl) and ^1H and ^{13}C NMR spectra, inclusive of HMBC and NOE experiments. However, the absolute configuration remained to be established (**843**). The same compound was identified in the South African *S. brasiliensis* by GC/MS (**475**).

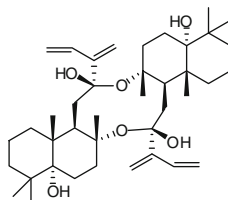
The ether extract of the Japanese *Scapania undulata* was fractionated by CC to afford the three new labdanes, $1\alpha,5\alpha,8\alpha$ -trihydroxy-(13*E*)-labden-12-one (**1290**), $5\alpha,8\alpha,9\alpha$ -trihydroxy-(13*E*)-labden-12-one (**1291**), and $5\alpha,8\alpha$ -dihydroxy-(13*E*)-labden-12-one (**1292**), and two novel dimeric labdanes, scapaundulins A (**1293**) and B (**1294**) (**973**). The absolute configuration of **1291** was established by a combination of its X-ray crystallographic analysis and CD difference spectroscopy before and after addition of $\text{Eu}(\text{fod})_3$ to a CCl_4 solution. The 8,9-diol showed a positive *Cotton* effect at 301 nm, corresponding to a positive chirality between the glycolic hydroxy groups. The structures of the other two labdanes were assigned by comparison of their NMR spectra with those of **1291** and detailed analyses of their 2D-NMR spectra. The structures of the two dimers ($\text{C}_{32}\text{H}_{48}\text{O}_6$ for **1293** and $\text{C}_{40}\text{H}_{64}\text{O}_6$ for **1294**) were arrived at by HRCIMS analysis, and from the IR (1740 cm^{-1} for **1293** and 3355 cm^{-1} for **1294**) and UV spectra (218 nm for **1293** and 220 nm for **1294**) as well as 2D-NMR spectroscopic analysis. The ^{13}C NMR spectra of scapaundulins A (**1293**) and B (**1294**) exhibited only 16 and 20 signals, indicating that **1293** and **1294** are symmetrical dimeric compounds. The homotropic monomeric structure of both compounds was deduced from careful analysis of the 2D-NMR spectra, employing COSY, NOESY, HSQC, and HMBC experiments. Comparison of the ^{13}C NMR chemical shifts of C-8 in the symmetrical dimers (**1293** and **1294**, δ_{C} 86.5 and 83.0 ppm) with those of compounds **1290–1292** (δ_{C} 77.4–74.0 ppm), proved to be the most important key point in the deduction of these dimeric structures. The two identical monomeric units confirmed by 2D-NMR spectroscopy could be connected *via* carbonyl linkages and/or hemiacetal linkages from C-8 of one half to C-11 of the other half. Thus, the ^{13}C NMR chemical shifts of C-8 in both dimers appeared at lower field than in **1290–1292**. Consequently, the structures of **1293** and **1294** possess C_2 symmetry, which gives rise to the homotropic behavior of the NMR spectra. The assigned structures were also in agreement with the unsaturation degree from the molecular formulas, and the compounds possess a central ten-membered ring connecting the two labdane moieties.



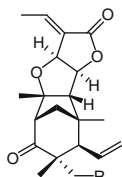
1290 $R^1=H$, $R^2=OH$ (1 α ,5 α ,8 α -trihydroxy-(13*E*)-labden-12-one)
1291 $R^1=OH$, $R^2=H$ (5 α ,8 α ,9 α -trihydroxy-(13*E*)-labden-12-one)
1292 $R^1=R^2=H$ (5 α ,8 α -dihydroxy-(13*E*)-labden-12-one)



1293 (scapandulin A)

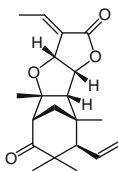


1294 (scapandulin B)

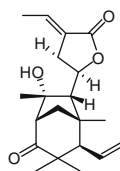


1295 $R=H$ (pallavicinin)

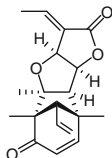
1296 $R=OH$ (18-hydroxy-pallavicinin)



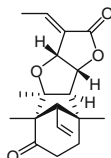
1297 (neopallavicinin)



1298 (8 α -hydroxy-3-oxo-8(7-2)abeo-6,(13*E*)-labdadien-16,11-olide)



1299 ((11 α H,12 α H)-8,12-epoxy-3-oxo-19-nor-8((7-4)abeo-(1*Z*,6,13*E*)-labdatrien-16,11-olide)

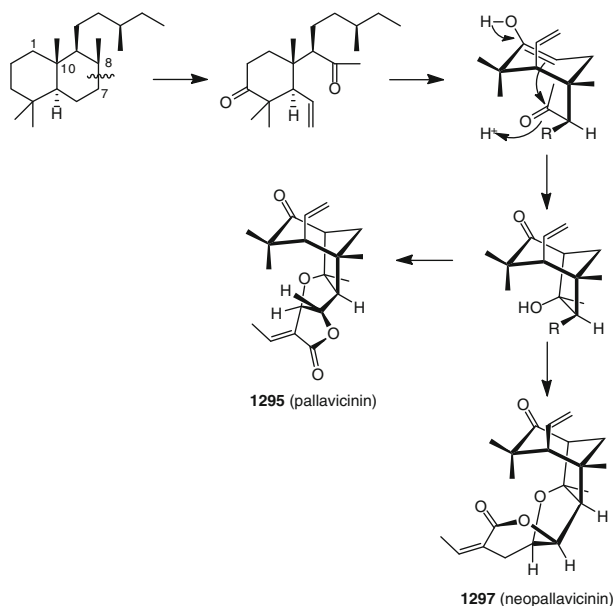


1300 ((11 β H,12 β H)-8,12-epoxy-3-oxo-19-nor-8((7-4)abeo-6,(13*E*)-labdadien-16,11-olide)

Labdane-type diterpenoids found in the Marchantiophyta

Wu and associates isolated the rearranged labdane pallavicinin (**1295**) from the ethyl acetate extract of the Taiwanese *Pallavicinia subciliata* (949, 954). This species also elaborates neopallavicinin (**1297**), the *cis*-isomer of pallavicinin (**1295**). The structure of **1295** was determined by X-ray crystallographic analysis (954). The NMR spectra of both **1295** and **1297** were closely comparable, but the retention times by GC were different. The final structure of **1297** was settled by the careful analysis of its NOESY spectrum (475). The volatile component of an unidentified *Pallavicinia* species collected in Borneo was investigated, and pallavicinin (**1295**) was identified (490).

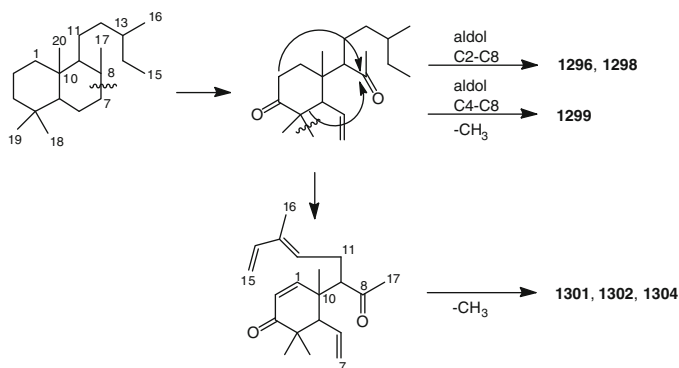
Neopallavicinin (**1297**) was also isolated from the Chinese *P. ambigua* together with the known pallavicinin (**1295**) and 18-hydroxypallavicinin (**1296**) (475). The structure of **1297** was determined by X-ray crystallographic analysis. The CD spectra of **1297** and **1295** both showed a negative *Cotton* effect at 304 nm. This



Scheme 4.42 Formation of rearranged labdane-type diterpenoids

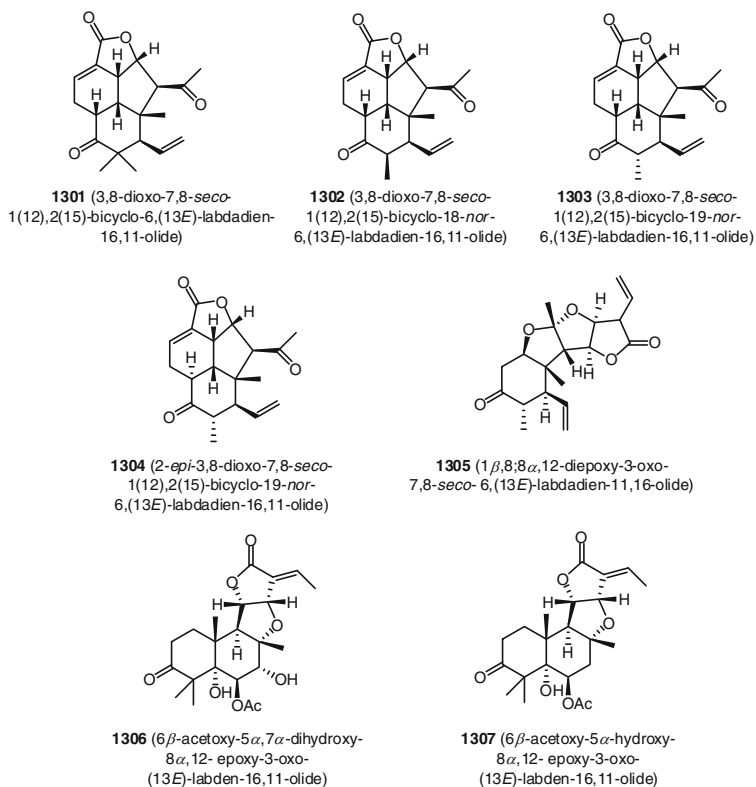
corroborated the fact that both labdanes **1297** and **1295** possess the same configuration with respect to the cyclohexane ring as reported for compound **1296** (see below). Compound **1297** showed a negative *Cotton* effect at ca. 225 nm, assignable to the $\pi - \pi^*$ transition of the lactone moiety. In contrast, compounds **1295** and **1296** displayed a positive *Cotton* effect at 230 nm, indicating that these two labdanes possess an inverted fusion geometry relative to **1297**. The presence of the positive *Cotton* effect of **1297** at 250 nm ($n - \pi^*$) supported the *cis*-fusion of the γ -lactone. A possible biogenesis pathway for **1295** and **1297** has been proposed (Scheme 4.42) (468).

The Japanese *Pallavicinia subciliata* is named “Kumonosu goke”, which translates to “spider nest-like liverwort”, since it completely changes its form to that of a thin black film as a result of being dried. This liverwort is chemically quite different from the other Metzgeriales species because it produces highly oxygenated rearranged labdane diterpenoids. The ether extract of *P. subciliata* resulted in the isolation of the 12 rearranged labdanes **1295**, **1296**, and **1298–1307** (702, 887). The structure of **1296** in having a hydroxy group at C-18 was assigned readily as 18-hydroxypallavicinin, by comparison of its spectroscopic data with those of **1295** and by X-ray crystallographic analysis. The same compound was obtained from *P. subciliata* collected in Taiwan (468). The structure of **1299** was established by X-ray crystallographic analysis. In turn, the structures of **1298**, **1300–1302**, and **1304** were assigned by the determination of their molecular formulas obtained by high-resolution MS and by comparison of their respective spectroscopic data with those of **1295**, **1296**, and **1299** as well as from the extensive analysis of their COSY, HMBC, and NOESY spectra. The structures of the other rearranged labdanes, **1303**,

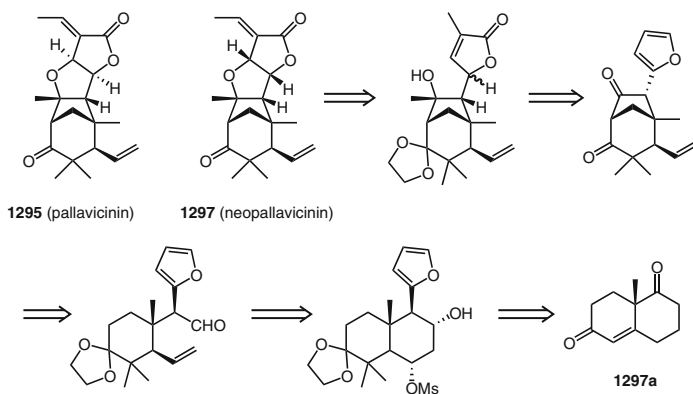


Scheme 4.43 Formation of rearranged labdane-type diterpenoids

and **1305–1307**, were also established by analysis of their 2D-NMR data (COSY, NOESY, HMQC, and HMBC). These unusual highly oxygenated rearranged labdanes might be biosynthesized by bond reconstruction of C-15/C-2 and C-12/C-1 for compounds **1301**, **1302**, and **1304**, and of C-8/C-2 or C-8/C-4 for **1296**, **1298**, and **1299**, after cleavage, as shown in Scheme 4.43.



Labdane-type diterpenoids found in the Marchantiophyta



Scheme 4.44 Retro synthesis of rearranged labdane-type diterpenoids

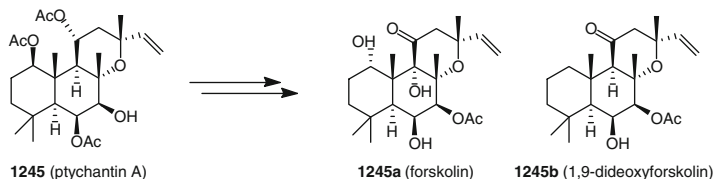
Racemic pallavicinin (**1295**) and neopallavicinin (**1297**) were synthesized for the first time from the racemic *Wieland-Miescher* ketone (**1297a**), via *Grob* fragmentation, intramolecular aldol cyclization, followed by an intramolecular *Michael* reaction, in 32 steps and in 0.1 and 0.007% overall yields, as shown in Scheme 4.44 (649).

Pleuroziol (**1308**), which was found for the first time in *Pleurozia gigantea*, was also isolated from the Malaysian *Jungermannia truncata* (136).

The three new labdane epoxides **1309–1311** were isolated from *Frullania hamatiloba*. This liverwort is very characteristic chemically since it produces the epoxides of labdanes as well as fusicocanes (316).

The ether extract of *Jamesoniella autumnalis* was fractionated by CC and Sephadex LH-20 to afford the three new labdanes **1312–1314** along with 19-acetoxy-*ent*-labda-8(17),(12*E*),14-trien-3 α -ol (**1315**) (811). The structures of the new compounds were elucidated by comparison of their spectroscopic data with those of **1315**. The spectroscopic data of **1313** were identical to those of 3 α -acetoxy-labda-8(17),(12*E*),14-triene, isolated from the higher plant *Palafoxia rosea*, but the optical rotation was different (119). The ^1H NMR spectrum of **1314** agreed with that of 3 α -hydroxy-*ent*-labda-8(17),(12*E*),14-trien-19-ol, previously isolated from *Mikania alvimii* (121). However, the chemical shifts of H-18 and H-19 of **1314** differed from those given in literature (121). Therefore, it was suggested that **1314** is 3 α -hydroxy-*ent*-labda-8(17),(12*E*),14-trien-18-ol. This was supported by the observation of a NOE interaction between H-19 and H-2a.

Ptychanthus striatus is a rich source of labdane diterpenoids, like ptychantins A-C (**1245–1247**) (40, 320). Hagiwara and associates synthesized forskolin (**1245a**), an activator of adenylate cyclase and 1,9-dideoxyforskolin (**1245b**), an inhibitor of glucose transport, using ptychantin A (**1245**), in 12 steps and 12% overall yield and eight steps and 35% overall yield (Scheme 4.45) (278, 279). A more expedient synthetic transformation to forskolin (**1245a**) from both ptychantins A (**1245**) and B (**1246**) was achieved by the same investigators,



Scheme 4.45 Hemisynthesis of forskolins from ptychantin A

by protection of the hydroxy groups at C-10 and C-11 by 2,2-dimethoxypropane after reduction of ptychantins A and B with LiAlH_4 , followed by protection of the other hydroxy groups at C-6 and C-7, using phosgene to provide the carbonate. Further deprotection of the acetonide, followed by hydroxylation at C-9 using *m*-chloroperbenzoic acid, and further deprotection of the carbonate gave forskolin (**1245a**) in 11 steps, with a 17% yield (280, 281).

4.3.9 Phytanes

The ether extract of the European *Pellia epiphylla* was purified by CC and HPLC to yield phytol (**1316**), 12,14-dihydroxyphytol (**1317**), and geranyl geraniol (**1319**) (176). Phytol (**1316**) was isolated from the ether extract of *Porella platyphylla* (583). The Taiwanese *Plagiochila elegans* contains phytol (**1316**) and phytadienes (**1320**) (470).

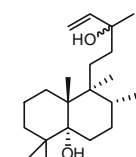
The diterpene phytol (**1316**) has been shown to be biosynthesized from methylerythritol *via* the phosphate pathway (MEP), as deduced by an incorporation experiment of ^{13}C labeled glucose into phytol. The labeling profile of (2*E*)-phytol (**1316**) from *T. tomentella* is in good agreement with that obtained from the liverworts *Ricciocarpos natans* and *Conocephalum conicum* (99, 989). Thiel and Adam further studied the biosynthesis of phytol (**1316**) and bornyl acetate (**58**), which are found in *Conocephalum conicum*, using $[1-^{13}\text{C}]1\text{-deoxy-D-xylose}$. Significant incorporation of this substrate was observed only in phytol, suggesting that there are two independent compartments in the MEP pathway in *C. conicum*, with the biosynthesis of phytol localized in the chloroplasts of the green cells of the thallus (831). A biosynthesis experiment of (2*E*)-phytol (**1316**) was also carried out by incorporation of $[1-^{13}\text{C}]$ -labeled glucose into axenic cultures of the Arctic *Fossombronia alaskana*. The labeling pattern obtained from the quantitative analysis of ^{13}C NMR spectroscopic analysis showed that the isoprene units of **1316** are derived from the methylerythritol phosphate pathway (339).

The biosynthesis pathway of the phytyl side chain of chlorophyll using ^{13}C -labeled serine ($[1-^{13}\text{C}]$ - and $[3-^{13}\text{C}]$ -) was reported by Itoh and associates using the cultured cells of the liverwort, *Heteroscyphus planus*. The labeling pattern in the isoprenoid unit of the ^{13}C -labeled phytol side chain corresponded to those expected from a non-mevalonate pathway (MVP). ^{13}C -labeled serine is one of

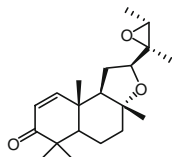
the most useful probes to determine the origin of terpene biosynthesis in MVP or non-MVP in the liverworts and other plant groups (366).

The ether extract of the sporophytes of *Pellia epiphylla* was purified by CC to give 1,2-bis-*nor*-phytone (**1318**) (175). The same compound was also isolated from the dichloromethane extract of the spores of *P. epiphylla*. Compound **1318** has already been found in the liverwort *Nardia scalaris* (40). *Tylimanthus renifolius* produces a phytene triol, with its structure characterized as (2*Z*)-phytene-1,15,20-triol (**1321**) on the basis of comparison of the NMR spectra obtained with those of phytol (**1316**) (213).

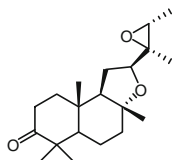
The New Zealand *Jamesoniella tasmanica* produces not only *epi*-neoverrucosane and *epi*-neohomoverrucosane diterpenoids but also 1,10,14-phytatrien-6,7-epoxy-3-ol (**1322**), for which the structure was established by a combination of 1D-NMR spectroscopic data interpretation and ¹H NMR irradiation experiments (616). Naviculide (**1323**) was isolated from the ether extract of the North American *Porella navicularis* (143).



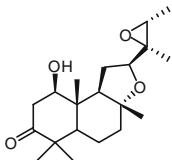
1308 (pleuroziol)



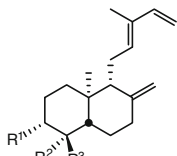
1309 (8,12:13,14-diepoxy-labd-1-en-3-one)



1310 (8,12:13,14-diepoxy-labd-3-one)



1311 (8,12:13,14-diepoxy-labd-1β-ol-3-one)

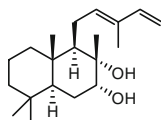


1312 R¹=OAc, R²=CH₂OH, R³=CH₃
(3α-acetoxy-*ent*-labda-8(17),(12*E*),14- trien-19-ol)

1313 R¹=OAc, R²=R³=CH₃
(3α-acetoxy-*ent*-labda-8(17),(12*E*),14- triene)

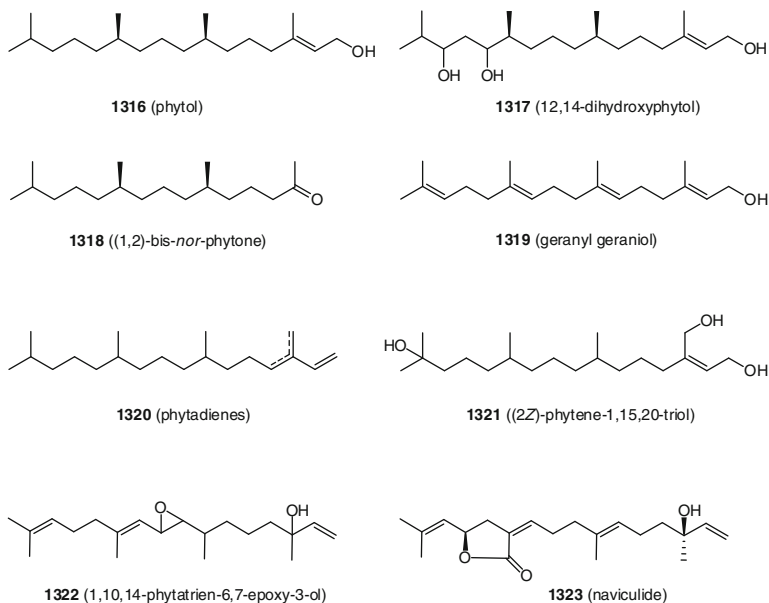
1314 R¹=OH, R²=CH₃, R³=CH₂OH
(3α-hydroxy-*ent*-labda-8(17),(12*E*),14- trien-18-ol)

1315 R¹=OH, R²=CH₂OAc, R³=CH₃
(19-acetoxy-*ent*-labda-8(17),(12*E*),14- trien-3α-ol)



1315a (labda-12,14-dien-7α,8α-diol)

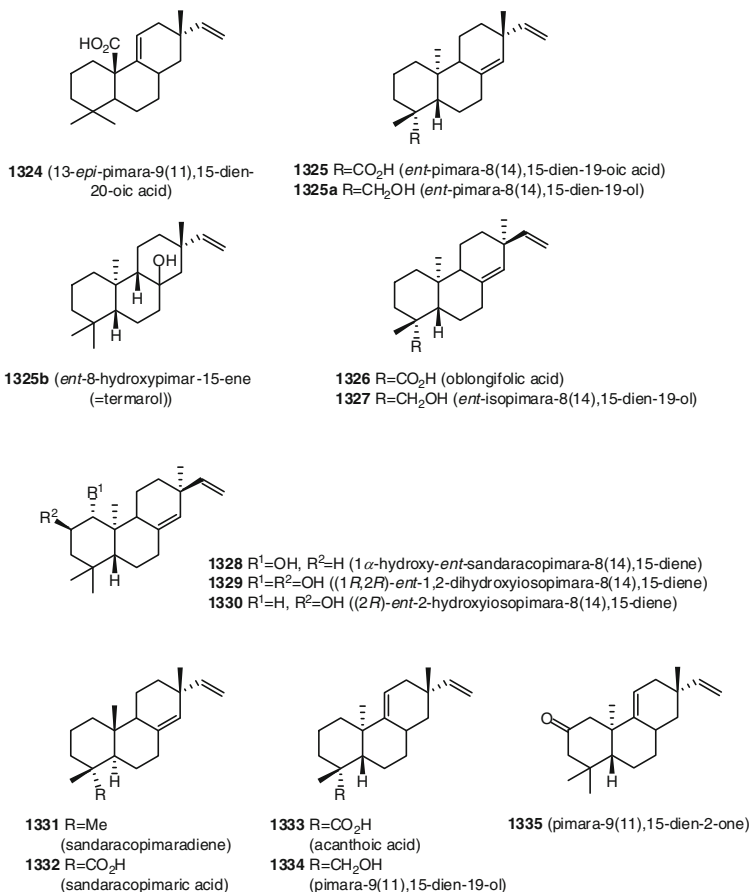
Labdane-type diterpenoids found in the Marchantiophyta



Phytane-type diterpenoids found in the Marchantiophyta

4.3.10 Pimaranes

The occurrence of pimarane diterpenoids in liverworts is very rare. Thus, *ent*-pimara-8(14),15-dien-19-ol (**1325a**) and *ent*-8-hydroxypimar-15-ene (**1325b**) have been found in *Jungermannia thermanum* (949). The ether extract of the New Zealand *Cuspidatula monodon* (Jungermanniaceae) was purified by CC to give a new pimarane diterpene for which the relative stereostructure was elucidated as 13-*epi*-pimara-9,15-dien-20-oic acid (**1324**), from the analysis of a combination of its 1D- and 2D-NMR spectroscopic data, including DEPT, HMBC, and NOESY measurements (72, 616).



Pimarane-type diterpenoids found in the Marchantiophyta

From the ether extract of the Japanese *Jungermannia hattoriana*, pimara-8-(14),15-dien-19-oic acid (**1325**) was isolated. The absolute configuration of **1325** was established by X-ray crystallographic analysis of its *p*-bromophenacyl derivative (**590**). The same compound (**1325**) was also found in the New Zealand *Bazzania novae-zelandiae* (**323**), *Dendromastigophora flagellifera* (**72**, **635**), the Madagascan *Mastigophora diclados* (**287**), and *Jungermannia thermarum* (**40**). Compound **1325** has also been isolated from the Japanese *Herbertus sakuraii*, representing the first isolation of a pimarane diterpenoid from the Herbertaceae (**323**, **365**).

The New Zealand *Jamesoniella kirkii* produces the *ent*-pimaranes **1326** and **1327**. The structure of **1326** (oblongifolic acid) was determined on the basis of NMR spectroscopy and X-ray crystallographic analysis (**612**). The chloroform extract of the New Zealand *Trichocolea mollissima* was fractionated by flash CC to give 1α-hydroxy-*ent*-sandaracopimara-8(14),15-diene (**1328**). The confirmation of the structure of **1328** was deduced by a combination of ¹³C and COSY NMR spectroscopic data analysis (**483**). The further investigation of the ether extract of the New Zealand *T. mollissima* resulted in the isolation of the two *ent*-isopimarane

diterpenoids **1329** and **1330** along with 1α -hydroxy-*ent*-sandaracopimara-8(14),15-diene (**1328**) (605). The structure of **1329** was assigned as $1\alpha,2\beta$ -dihydroxyisopimara-8(14),15-diene by 2D-NMR (COSY, HMBC, and NOESY) methods. The absolute configuration of the alcohol at C-2 was determined to be (*R*) by the modified Mosher method. Thus, the complete structure of **1329** is (*1R,2R*)-*ent*-1,2-dihydroxyisopimara-8(14),15-diene. The ^1H - and ^{13}C NMR data of **1330** resembled those of **1328** and **1329**, indicating that **1330** is also an isopimarane diterpenoid. The analysis of its 2D-NMR spectra (COSY, HMQC, and HMBC) clarified that the structure of **1330** corresponds to 2-hydroxyisopimara-8(14),15-diene. The orientation of the 2-hydroxy group at C-2 was determined to be β by means of a NOESY experiment. Oxidation of **1330** gave a ketone, which showed a negative Cotton effect at 294 nm. Thus, the absolute configuration of **1330** was deduced as (*2R*)-*ent*-2-hydroxyisopimara-8(14),15-diene. The absolute configuration of compound **1328** still remained to be clarified. Esterification of **1328** with *m*-bromobenzoic acid gave its *m*-bromobenzoate. X-ray crystallographic analysis confirmed the absolute configuration of **1328** to be 1α -hydroxy-*ent*-sandaracopimara-8(14),15-diene.

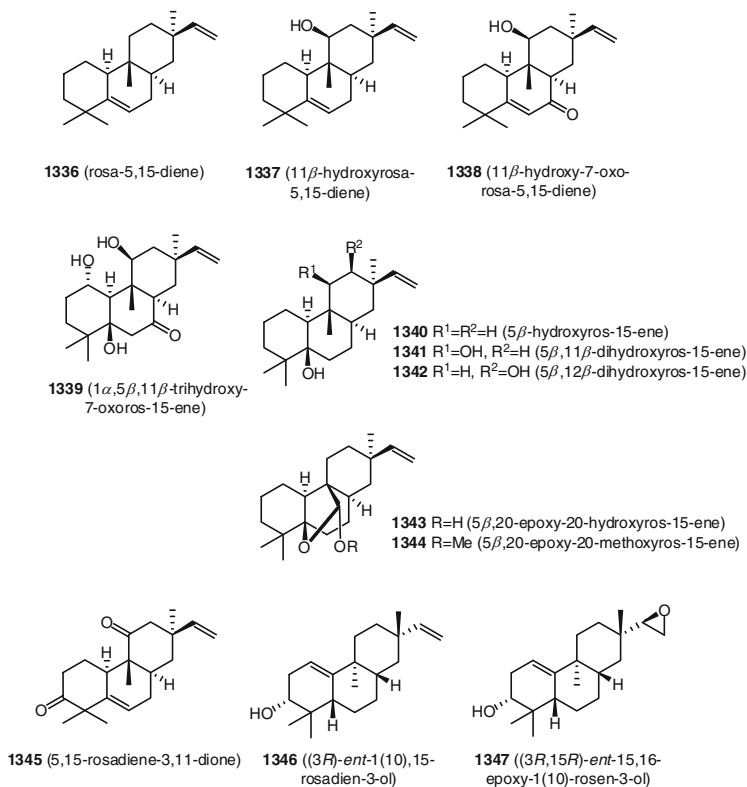
The pimarane, sandaracopimaradiene (**1331**), was obtained from an ether extract of the North American *Porella navicularis*. This diterpene was at the time of its isolation newly identified among the liverworts (143). *Mastigophora dicladus* biosynthesizes (–)-sandaracopimaric acid (**1332**) together with the above-mentioned *ent*-pimara-8(14),15-dien-19-oic acid (**1325**) (287). The pimarane, acanthoic acid (**1333**), was isolated from the New Zealand *Plagiochila deltoidea* (607).

Pimara-9(11),15-dien-19-ol (**1334**) was isolated from the crude extract of the Malaysian *Jungermannia truncata* (136). This is the first report of the isolation of **1334** from liverworts, although this compound has been found also in the higher plant, *Acanthopanax koreanum* (411). Fractionation of the ether extract of the New Zealand *Chiloscyphus mittenianus* led to the isolation of the new *ent*-pimarane diterpene ketone **1335**, for which the structure was established as 9(11),15-pimaradien-2-one by COSY, HMBC, and NOESY experiments. Its absolute configuration and conformation determinations were based on MOE calculations and the CD spectrum, which showed a negative Cotton effect at 298 nm. This is the first isolation of diterpenoids from the genus *Chiloscyphus* (347).

4.3.11 Rosanes

The distribution of rosane diterpenoids is restricted to only some liverworts. Rosa-5,15-diene (**1336**) was isolated from the ether extract of the North American *Porella navicularis* (143). This diterpene was at the time newly identified among the liverworts. The ether extract of *Gackstroemia decipiens* was purified by HPLC to afford the six new rosane diterpenoids, 11β -hydroxy-7-oxorosa-5,15-diene (**1338**), $1\alpha,5\beta,11\beta$ -trihydroxy-7-oxoros-15-ene (**1339**), $5\beta,11\beta$ -dihydroxyros-15-ene (**1341**), $5\beta,12\beta$ -dihydroxyros-15-ene (**1342**), $5\beta,20$ -epoxy-20-hydroxyros-15-ene (**1343**), and $5\beta,20$ -epoxy-20-methoxyros-15-ene (**1344**), together with 11β -hydroxyrosa-5,15-diene (**1337**) and 5β -hydroxyros-15-ene (**1340**) (251), which are enantiomers of compounds isolated from higher plants (123, 245). The

absolute stereostructures of all the isolated compounds obtained for the first time were determined by analysis of their 2D-NMR (HMBC, NOESY) spectra.



Rosane-type diterpenoids found in the Marchantiophyta

Tylimanthus renifolius produces a new rosadienedione, for which the structure was settled as 5,15-rosadiene-3,11-dione (**1345**) by 2D-NMR analysis and Cotton effect measurement (213). The New Zealand collection of *Plagiochila deltoidea* elaborates two *ent*-rosane diterpenoids. The absolute stereochemistry of both compounds was established as (3*R*)-*ent*-1(10),15-rosadien-3-ol (**1346**) and (3*R*,15*R*)-*ent*-15,16-epoxy-1(10)-rosen-3-ol (**1347**), by a combination of 2D-NMR data interpretation and X-ray crystallographic analysis of the *m*-bromobenzoate of **1346** and the *p*-bromobenzoate of **1347** (607).

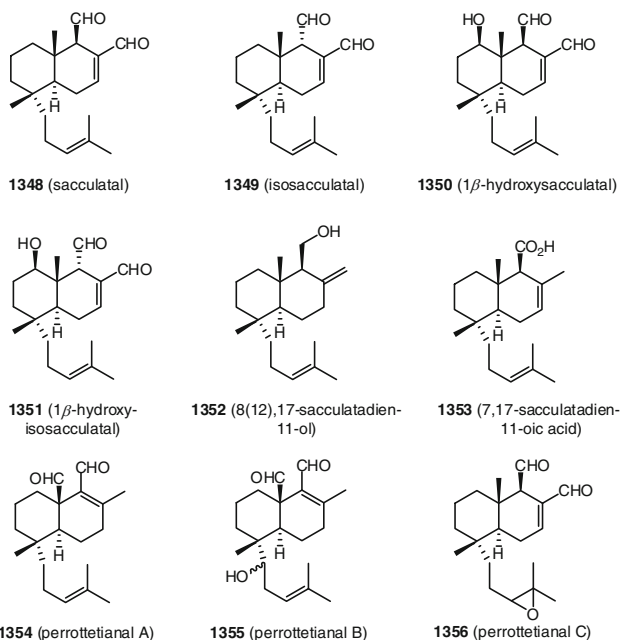
4.3.12 *Sacculatanes*

Sacculatane diterpenoids are very rare in Nature and are still restricted only to the Marchantiophyta. *Pellia endiviifolia* (Fig. 4.18) is a rich source of sacculatane



Fig. 4.18 *Pellia endiviifolia*

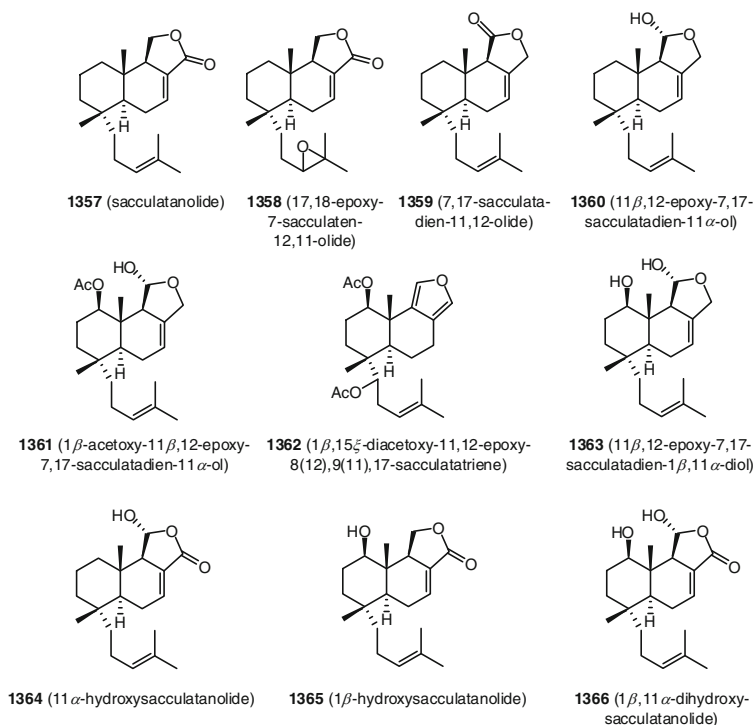
diterpenoids (40). In addition to the known sacculatal (1348) and isosacculatal (1349), the isolation and structure determination of 11 β ,12-epoxy-7,17-sacculatadien-1 β ,11 α -diol (1363), 11 α -hydroxysacculatanolide (1364), 1 β ,11 α -dihydroxysacculatanolide (1366), 1 β -hydroxyisosacculatal (1351), 1 β -hydroxysacculatanolide (1365), and sacculatanolide (1357) were reported (40). Detailed structure elucidation proposals for these compounds were achieved by a combination of chemical reaction, 2D-NMR spectroscopy, and X-ray crystallographic (for 1363) and Cotton effect determinations. Furthermore, pellianolactones A (1367) and B (1368) and 1 β -hydroxysacculatal (1350) were isolated from the same liverwort and determined using the same methods as mentioned above, including X-ray crystallographic analysis for 1367 (311). Hashimoto and associates reported also the isolation of the four new sacculatanes, pellianolactone C (1369), pellianolactol (1370), 11,12-epoxy-8(12),9-(11),17-sacculatatriene (1371), and 11 β ,12-epoxy-17-sacculaten-11 α -ol (1372) from the Japanese *Pellia endiviifolia*. Their stereostructures were established by CD and 2D-NMR spectroscopic data interpretation (312).



Sacculatane-type diterpenoids found in the Marchantiophyta

A biosynthetic experiment on sacculatal (**1348**) was carried out by incorporation of [1- ^{13}C]-labeled glucose into axenic cultures of the Arctic *Fossombronia alaskana*. Quantitative ^{13}C NMR spectroscopic analysis of the resulting labeled profiles indicated that the isoprene units of **1348** are derived from the methylerythritol phosphate pathway (**339**).

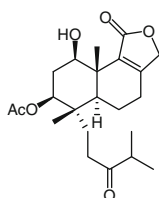
Fractionation of the dichloromethane extract of axenic cultures of the liverwort *Fossombronia wondraczekii* led to the isolation of the five new sacculatane diterpenoids, 17,18-epoxy-7-sacculaten-12,11-olide (**1358**), 7,17-sacculatadien-11,12-olide (**1359**), 11 β ,12-epoxy-7,17-sacculatadien-11 α -ol (**1360**), 1 β -acetoxy-11 β ,12-epoxy-7,17-sacculatadien-11 α -ol (**1361**), and 1 β ,15 ξ -diacetoxy-11,12-epoxy-8(12),9(11),17-sacculatatriene (**1362**), together with the known sacculatal (**1348**) and sacculatanolide (**1357**) (**339**). The stereostructures of the new compounds were settled mainly by analysis of their 2D-NMR spectroscopic data. The absolute configuration of each compound was the same as that of sacculatal (**1348**) (**216**, **339**), which displays a negative optical rotation (**39**, **40**).



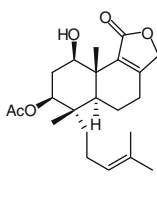
Sacculatane-type diterpenoids found in the Marchantiophyta

The German *Pellia endiviifolia* was analyzed by GC/MS to identify sacculatal (**1348**) as the major component, together with sacculanolide (**1357**) and 7,17-sacculatadien-11,12-olide (**1359**) (492), which has been found in *Fossombronia wondraczekii* (216). *P. epiphylla* also contains sacculatal (**1348**), isosacculatal (**1349**), sacculanolide (**1357**), and its isomer, **1359** (492). Thus, *P. endiviifolia*, *P. epiphylla* and *F. wondraczekii* are very closely related chemically.

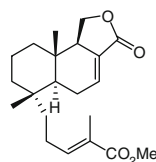
The ether extract of the European *Pellia epiphylla* was purified by CC and HPLC to yield the new 8(12),17-sacculatadien-11-ol (**1352**) and 7,17-sacculatadien-11-oic acid (**1353**) (176), along with the known sacculaporellin (**1373**) (66, 138). The structures of **1352** and **1353** were elucidated from their 2D-NMR spectroscopic data.



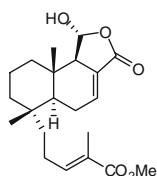
1367 (pellianolactone A)



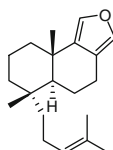
1368 (pellianolactone B)



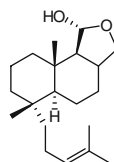
1369 (pellianolactone C)



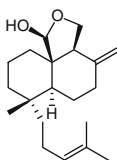
1370 (pellianolactol)



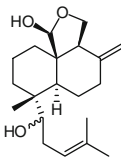
1371 (11,12-epoxy-8(12),9(11),17-sacculatriene)



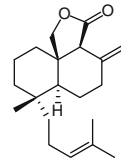
1372 (11β,12-epoxy-17-sacculaten-11α-ol)



1373 (sacculaporellin)



1374 ((13S)-15ξ-hydroxy-sacculaporellin)



1375 (8(12),17-sacculatadien-11,13-olide)

Sacculatane-type diterpenoids found in the Marchantiophyta

Perrottetianal A (**1354**), the isomer of sacculatal (**1348**), was obtained previously from *Porella perrottetiana* as the major component (**40**). The same dialdehyde was isolated not only from the Jungermanniales but also the Metzgeriales; from *Porella acutifolia* subsp. *tosana* (**316**, **322**), *Porella grandiloba* (**814**), *Plagiochila ovalifolia* (**701**), *Makinoa crispata* (**492**), the New Zealand *Lepidozia macrophylla*, *Porella elegantula* (**72**, **616**), and *Paraschistochila pinnatifolia* (**84**). *M. crispata* and *P. elegantula* each produce a large amount (over 30% yield for the crude extract) of perrottetianal A (**1354**). From the ether extract of *Porella platyphylla* (**583**) and *P. grandiloba* (**814**) perrottetianal B (**1355**) was isolated. While the structure of **1355** was assigned as 3-hydroxyperrottetianal A (**40**), the position of the secondary alcohol was revised as being located at C-15 from HSQC, HMBC, and NOESY spectroscopic information. Thus, the structure of **1355** was re-assigned as 15ξ-hydroxyperrottetianal A (**583**).

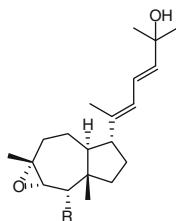
The ether extract of the New Zealand *Marchantia foliacea* was purified by a combination of CC, passage over Sephadex LH-20, and HPLC to afford a new sacculatane diterpenoid named perrottetianal C (**1356**). The structure of **1356** was deduced by the comparison of its spectroscopic data with those of perrottetianal A (**1354**) (**347**).

Further fractionation of the methanol extract of the English *Porella platyphylla* resulted in the isolation of the new sacculatane, (13S)-15ξ-hydroxysacculaporellin

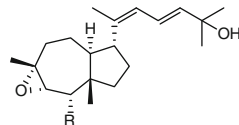
(**1374**), along with perrottetianal B (**1355**) (*138*). The structure of **1374** was assigned as the sacculatane hemiacetal, (5*S*,9*S*,10*R*,13*S*)-11,13-epoxy-8(12),17-sacculatadiene-13 β ,15 ξ -diol, by extensive analysis of its NMR data including NOE correlations, and by comparison with analogous values for (13*S*)-hydroxysacculaporellin (**1374**), isolated from the Japanese *Porella perrottetiana* (*40*). *Buchanan* and colleagues revised the absolute configuration at C-13 of sacculaporellin **1374** from (13*R*) to (13*S*), as a result of the NOE correlation data obtained for this compound (*138*). *Paraschistochila pinnatifolia* elaborates a new sacculatadienolide, for which the structure was assigned tentatively as 8(12),17-sacculatadien-11,13-olide (**1375**) (*84*).

4.3.13 *Sphenolobanes*

The distribution of sphenolobane diterpenoids is restricted to the *Anastrophyllum* liverworts (*40*). The ether extract of the Ecuadorian *Anastrophyllum auritum* was fractionated by CC, MPLC, and HPLC to give the seven new sphenolobane diterpenoids, 3 α ,4 α -epoxy-18-hydroxysphenoloba-(13*E*(15),16*E*)-diene (**1376**), 3 α ,4 α -epoxy-18-hydroxysphenoloba-(13*Z*(15),16*E*)-diene (**1378**), 3 α ,4 α -epoxy-5 α ,18-dihydroxysphenoloba-(13*Z*(15),16*E*)-diene (**1379**), 3 α ,4 α -epoxysphenoloba-(13*E*(15),16*E*,18)-triene (**1380**), 3 α ,4 α -epoxy-5 α -hydroxysphenoloba-(13*E*(15),16*E*,18)-triene (**1381**), 3 α ,4 α -epoxy-5 α -hydroxysphenoloba-13,(15*E*),17-triene (**1382**), and 3 α ,4 α -epoxysphenoloba-(13*E*(15),17)-diene (**1383**) (*976*), together with the known 3 α ,4 α -epoxy-5 α ,18-dihydroxysphenoloba-(13*E*(15),16*E*)-diene (**1377**) (*40*). The structure of **1376** was proven readily by means of comparison of its ^1H NMR spectroscopic values with those of the known epoxysphenolobane (**1377**) (*40*) and analysis of COSY data (^1H - ^1H and ^{13}C - ^1H). The configuration (13*E*(15),16*E*) of **1376** was also based on NOE measurements. The structures of **1378** and **1379** were established as geometrical isomers in the side chains of **1376** and **1377** as a result of NOE examination. The NMR spectra of **1380** and **1381** were very similar to those of **1376** and **1377**, except for the presence of an isopropenyl group in place of a dimethyl carbinol, establishing that **1380** and **1381** are dehydrated products of **1376** and **1377**. The structure of compound **1382** was deduced from the similarity of the spectroscopic data of compound **1381** and analysis of NOEs. The final assignment (13*E*(15),17) of the sphenolobane **1383** was proven using NOE measurements. The complete structure was settled by means of the detailed analysis of its ^1H NMR spectroscopic data. This was the second example of the isolation of sphenolobane diterpenoids from liverworts (*976*).



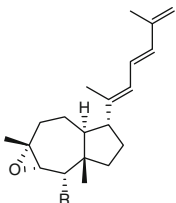
1376 R=H (3 α ,4 α -epoxy-18-hydroxysphenoloba-(13*E*(15),16*E*)-diene)



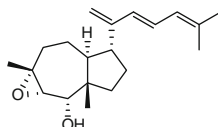
1378 R=H (3 α ,4 α -epoxy-18-hydroxysphenoloba-(13*Z*(15),16*E*)-diene)

1377 R=OH (3 α ,4 α -epoxy-5 α ,18-dihydroxysphenoloba-(13*E*(15),16*E*)-diene)

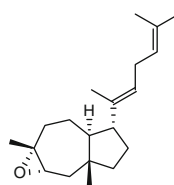
1379 R=OH (3 α ,4 α -epoxy-5 α ,18-dihydroxysphenoloba-(13*Z*(15),16*E*)-diene)



1380 R=H (3 α ,4 α -epoxysphenoloba-(13*E*(15),16*E*,18)-triene)

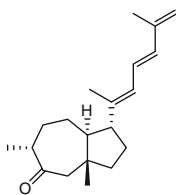


1382 (3 α ,4 α -epoxy-5 α -hydroxysphenoloba-(3,(15*E*),17)-triene)

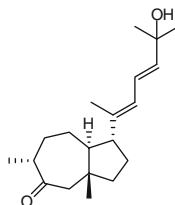


1383 (3 α ,4 α -epoxysphenoloba-(13*E*(15),17)-diene)

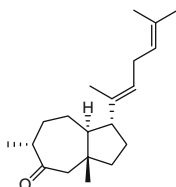
1381 R=OH (3 α ,4 α -epoxy-5 α -hydroxysphenoloba-(13*E*(15),16*E*,18)-triene)



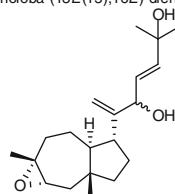
1384 ((3*R**,6*R**,9*R**,10*S**)-sphenoloba-(13*E*(15),16*E*,18)-trien-4-one)



1385 ((3*R**,6*R**,9*R**,10*S**)-18-hydroxysphenoloba-(13*E*(15),16*E*)-dien-4-one)



1386 ((3*R**,6*R**,9*R**,10*S**)-sphenoloba-(13*E*(15),17)-dien-4-one)



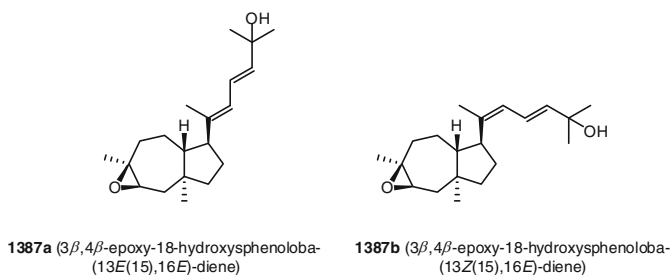
1387 ((6*R**,9*R**,10*S**)-3 α ,4 α -epoxysphenoloba-13(14),(16*E*)-dien-15,18-diol)

Sphenolobane-type diterpenoids found in the Marchantiophyta

Fractionation of the ether extract of the Scottish *Anastrophyllum donnianum* led to the isolation of the four new sphenolobanes, **1384–1387**, together with the two known sphenolobanes, (6*R**,9*R**,10*S**)-3 α ,4 α -epoxysphenoloba-(13*E*(15),16*E*)-dien-18-ol (**1376**) and (6*R**,9*R**,10*S**)-3 α ,4 α -epoxysphenoloba-(13*E*(15),17)-diene (**1383**). The structures of the new compounds were established as (3*R**,6*R**,9*R**,10*S**)-sphenoloba-(13*E*,16*E*,18)-trien-4-one (**1384**), (3*R**,6*R**,9*R**,10*S**)-18-hydroxysphenoloba-(13*E*,16*E*)-dien-4-one (**1385**), (3*R**,6*R**,9*R**,10*S**)-sphenoloba-(13*E*),17-dien-4-one (**1386**), and (6*R**,9*R**,10*S**)-3 α ,4 α -epoxysphenoloba-13(14),(16*E*)-dien-15,18-diol

(**1387**), using a combination of UV, IR, and 2D-NMR long-range correlation experiments inclusive of NOE, and comparison of the NMR values with those of the previously isolated sphenolobanes **1376** and **1383**. The absolute configuration of these compounds still remained to be clarified at the time of their isolation (*139*).

Nakashima and colleagues accomplished the total synthesis of (-)-3 β ,4 β -epoxy-18-hydroxysphenoloba-(13*E*(15),16*E*)-diene (**1387a**) and (-)-3 β ,4 β -epoxy-18-hydroxysphenoloba-(13*Z*(15),16*E*)-diene (**1387b**), employing the *Grubbs* catalyst to effect olefin metathesis, and clarified that the absolute configuration of the sphenolobanes isolated from liverworts is opposite to that found in such compounds when obtained from higher plants (*601*).



Sphenolobane-type diterpenoids synthesized by the authors of Ref. (*601*)

Sphenolobane diterpenoids have been found not only in liverworts, but also in marine organisms, such as the sponges *Epipolasis reisiwigi* (belonging to the order Halichondrida) (*392*) and an *Epipolasis* species (*907*), and the higher plant *Halimum viscosum* (*908*, *909*).

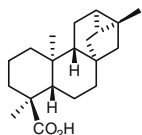
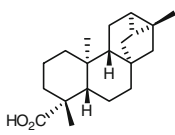
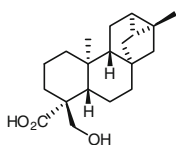
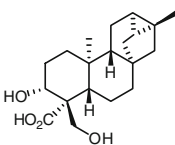
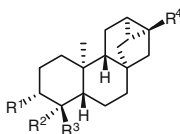
4.3.14 *Trachylobanes*

The trachylobanes are very rarely found in Nature and only *ent*-3 β ,18-dihydroxy-trachyloban-19-oic (**1390a**) acid has been isolated from *Jungermannia exsertifolia* subsp. *cordifolia* earlier (*40*).

The crude extract of the West Malaysian *Mastigophora diclados* was purified by CC to afford the new trachylobane, *ent*-18-hydroxytrachyloban-19-oic acid (**1390**) (*464*), along with the two known substances, *ent*-trachyloban-18-oic acid (**1388**) (*302*) and *ent*-trachyloban-19-oic acid (**1389**) (*162*, *212*). The structure of **1390** was settled by comparison of its 2D-NMR data with those of **1388** and **1389** as well as using NOE difference spectroscopy. Compound **1388** was also isolated from the ether extract of the New Zealand *Chiloscyphus mittenianus*, for which the structure was elucidated by COSY, HMQC, HMBC, and NOESY experiments (*347*).

From the dichloromethane extract of *J. exsertifolia* subsp. *cordifolia* collected in Switzerland, the eleven new trachylobane diterpenoids (**1390e–1390o**) possessing anti-*Mycobacterium tuberculosis* activity were isolated using a combination of vacuum-liquid chromatography, size-exclusion chromatography, and preparative HPLC, together with the three known trachylobanes, *ent*-3 β -hydroxytrachylobane

(**1390b**), *ent*-trachyloban-3-one (**1390c**), and *ent*-3 β -acetoxytrachylobane (**1390d**). The structures of the new trachylobanes were proven to be *ent*-3 β -acetoxy-18-hydroxytrachylobane (**1390e**), *ent*-18 α -acetoxy-3 β -hydroxytrachylobane (**1390f**), *ent*-3 β -acetoxy-19-hydroxytrachylobane (**1390g**), *ent*-3 β -acetoxytrachyloban-18-al (**1390h**), *ent*-3 β -acetoxytrachyloban-19-al (**1390i**), *ent*-3 β -acetoxy-17-hydroxytrachylobane (**1390j**), *ent*-17-hydroxytrachylobane (**1390k**), *ent*-trachyloban-17-al (**1390l**), *ent*-3 β ,18-diacetoxy-19-trachylobanoic acid (**1390m**), *ent*-3 β ,18 α -dihydroxytrachylobane (**1390n**), and *ent*-3 β -hydroxy-17-trachylobanoic acid (**1390o**), by a combination of the ^1H - and ^{13}C NMR and 2D-NMR spectroscopic experiments (COSY, HMBC, and NOESY) (717). Computational full-spin simulation analysis of the 900 MHz NMR spectrum of **1390b** and confirmation of the full assignment of ^1H NMR resonances including their multiplicities were performed using the PERCH spin simulation software from PERCH Solution Ltd., Kuopio, Finland (717).

1388 (*ent*-trachyloban-18-oic acid)1389 (*ent*-trachyloban-19-oic acid)1390 (*ent*-18-hydroxytrachyloban-19-oic acid)1390a (*ent*-3 β ,18-dihydroxytrachyloban-19-oic acid)

- 1390b** R¹=OH, R²=R³=R⁴=Me (*ent*-3 β -hydroxytrachylobane)
1390c R¹=O, R²=R³=R⁴=Me (*ent*-trachyloban-3-one)
1390d R¹=OAc, R²=R³=R⁴=Me (*ent*-3 β -acetoxytrachylobane)
1390e R¹=OAc, R²=R⁴=Me, R³=CH₂OH (*ent*-3 β -acetoxy-18-hydroxytrachylobane)
1390f R¹=OH, R²=R⁴=Me, R³=CH₂OAc (*ent*-18 α -acetoxy-3 β -hydroxytrachylobane)
1390g R¹=OAc, R²=CH₂OH, R³=R⁴=Me (*ent*-3 β -acetoxy-19-hydroxytrachylobane)
1390h R¹=OAc, R²=R⁴=Me, R³=CHO (*ent*-3 β -acetoxytrachyloban-18-al)
1390i R¹=OH, R²=CHO, R³=R⁴=Me (*ent*-3 β -acetoxytrachyloban-19-al)
1390j R¹=OAc, R²=R³=Me, R⁴=CH₂OH (*ent*-3 β -acetoxy-17-hydroxytrachylobane)
1390k R¹=H, R²=R³=Me, R⁴=CH₂OH (*ent*-17-hydroxytrachylobane)
1390l R¹=H, R²=R³=Me, R⁴=CHO (*ent*-trachyloban-17-al)
1390m R¹=OAc, R²=CO₂H, R³=CH₂OAc, R⁴=Me (*ent*-3 β ,18 α -diacetoxytrachyloban-19-oic acid)
1390n R¹=OH, R²=R⁴=Me, R³=CH₂OH (*ent*-3 β ,18 α -dihydroxytrachylobane)
1390o R¹=OH, R²=R³=Me, R⁴=CO₂H (*ent*-3 β -hydroxytrachyloban-17-oic acid)

Trachylobane-type diterpenoids found in the Marchantiophyta

Jungermannia exsertifolia subsp. *cordifolia* collected in the Vosges Mountains, France is a rich source of *ent*-kauranes and *ent*-seco-kauranes, as mentioned earlier

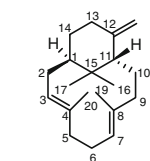
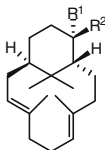
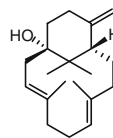
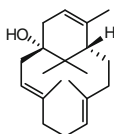
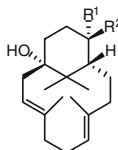
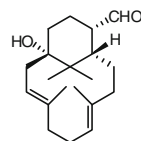
(586). However, neither *ent*-kauranes nor *ent*-seco kauranes were found in the same species when collected in Switzerland (717).

4.3.15 Verticillanes

Jackiella javanica is a rich source of the naturally occurring rare diterpenoids, the verticillanes. Previously, eight *ent*-verticillanes (**1392**–**1397**, **1401**, **1403**) were isolated from the Japanese *J. javanica* (40, 587). The enantiomer of **1392** was found as a constituent of a conifer tree (40). The stereostructure of *ent*-verticillanediol (**1396**) was established as a result of X-ray crystallographic analysis.

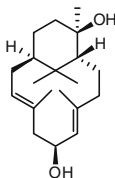
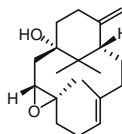
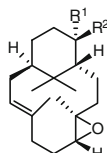
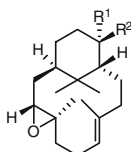
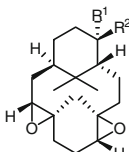
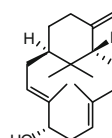
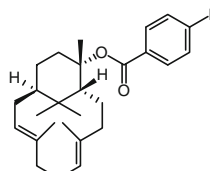
Further investigation of the above-mentioned sample of *J. javanica* resulted in the isolation of *ent*-verticilla-3,7,12-trien-1 α -ol (**1395**), (7*R*,8*R*,12*S*)-*ent*-7,8-epoxy-(3*E*)-verticillen-12-ol (**1402**), and (5*S*)-*ent*-verticilla-(3*E*,7*E*,12(18))-trien-5-ol (**1403**), together with the five known verticillanes, *ent*-verticillol (**1392**), *ent*-12-*epi*-verticillol (**1393**), *ent*-isoverticillenol (**1394**), *ent*-verticillanediol (**1396**), and *ent*-12-*epi*-verticillanediol (**1397**) (40). The structural determination of **1395** was based on X-ray crystallographic analysis. In turn, the structure of **1402** was confirmed by the formation of the several epoxy derivatives **1401**–**1402d** obtained by oxidation of a mixture of *ent*-verticillol (**1392**) and *ent*-12-*epi*-verticillol (**1393**) with *m*-chloroperbenzoic acid. The spectroscopic data of derivative **1401** were identical with those of the natural product (608).

Additional work-up of a crude extract of *J. javanica* resulted in the isolation of the *ent*-verticillanes **1398**–**1400**, together with *ent*-exo-verticillane (**1391**) (614). The structures of the newly isolated compounds were based on COSY, HMBC, and NOESY experiments. The absolute stereochemistry of the *ent*-verticillanes had been determined originally by comparison with the optical rotations of their enantiomeric verticillanes. However, Jin and associates reported the revision of the absolute configuration of (+)-verticillol isolated from the higher plant, *Sciadopitys verticillata*, from **1392** to **1403b** by X-ray crystallographic analysis of its *p*-iodobenzoate derivative (378). In order to confirm the absolute configuration of verticillanes obtained from a liverwort, *ent*-*epi*-verticillol *p*-iodobenzoate (**1403a**) was prepared. Its X-ray analysis showed clearly that the absolute stereochemistry at C-1 and C-11 are both (*R*) configured. Thus, *ent*-*epi*-verticillol should be revised from **1403c** to **1393**. The CD spectrum of **1392** also showed a negative Cotton effect, while (+)-verticillol (**1403b**) showed a positive one. The other *ent*-verticillanes **1394**–**1397**, **1399**, and **1403** displayed also a negative Cotton effect.

**1391** (*ent-exo*-verticillene)**1392** R¹=Me, R²=OH (*ent*-verticillol)
1393 R¹=OH, R²=Me (*ent*-12-*epi*-verticillol)**1394** (*ent*-isoverticillend)**1395** (*ent*-verticilla-3,7,12-trien-1β-ol)**1396** R¹=Me, R²=OH (*ent*-verticillanediol)
1397 R¹=OH, R²=Me (*ent*-12-*epi*-verticillanediol)**1398** ((1*S*,12*S*)-*ent*-1-hydroxy-verticilla-(3*E*,7*E*)-dien-18-al)

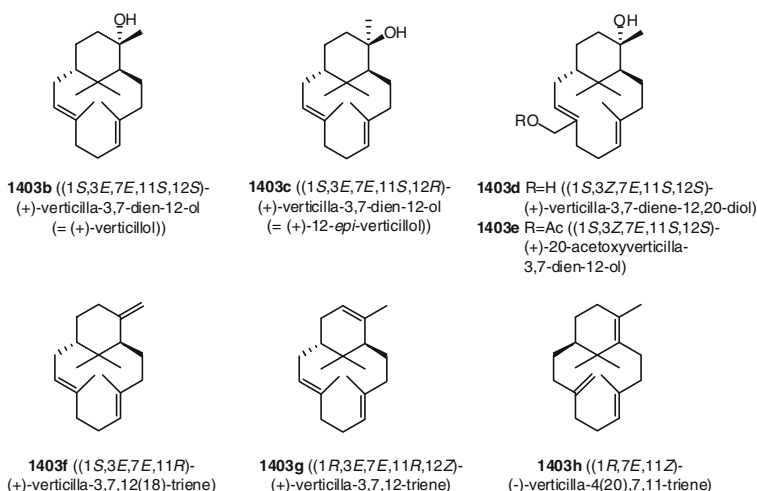
Verticillane-type diterpenoids found in the Marchantiophyta

Verticillanes, which have been proposed to be the biogenetic precursors of taxanes, are rare bicyclic diterpenoids. *Jin* and colleagues reported that the cyclization mechanism proceeds through a verticillane-12-yl carbocation intermediate. The absolute configuration of all verticillane diterpenoids previously isolated should therefore be reversed, on the basis of the anomalous dispersion X-ray analysis of (+)-verticillol *p*-iodobenzoate ([378](#)).

**1399** ((6*S*,12*R*)-*ent*-verticilla-3,7-dien-6,12-diol)**1400** ((1*S*,3*R*,4*R*)-*ent*-3,4-epoxy-verticilla-7,12(18)-dien-1-ol)**1401** R¹=Me, R²=OH ((7*R*,8*R*,12*R*)-*ent*-7,8-epoxy-(3*E*)-verticillen-12-ol)
1402 R¹=OH, R²=Me ((7*R*,8*R*,12*S*)-*ent*-7,8-epoxy-(3*E*)-verticillen-12-ol)**1402a** R¹=Me, R²=OH ((3*R*,4*R*,12*R*)-*ent*-3,4-epoxy-(7*E*)-verticillen-12-ol)**1402c** R¹=Me, R²=OH ((3*R*,4*R*,7*R*,8*R*,12*R*)-*ent*-3,4,7,8-diepoxyverticillan-12-ol)**1403** ((5*S*)-*ent*-verticilla-(3*E*,7*E*,12(18))-trien-5-ol)**1402b** R¹=OH, R²=Me ((3*R*,4*R*,12*S*)-*ent*-3,4-epoxy-(7*E*)-verticillen-12-ol)**1402d** R¹=OH, R²=Me ((3*R*,4*R*,7*R*,8*R*,12*S*)-*ent*-3,4,7,8-diepoxyverticillan-12-ol)**1403a** (*ent-epi*-verticillol *p*-iodobenzoate)

Verticillane-type diterpenoids found in the Marchantiophyta and their derivatives

The Mexican higher plants, *Bursera suntui* and *B. kerberi* are rich sources of verticillane diterpenoids. From these species, the seven new verticillanes, (+)-verticillol (**1403b**), (+)-12-*epi*-verticellol (**1403c**) and **1403d–1403h** were isolated, and their absolute configurations were determined by comparison of the optical rotatory dispersion spectrum of the recently revised **1403b** with those of *ent*-verticillanes isolated from *Jackiella javanica* (338). The essential oil of *Boswellia carterii* resinoid (olibanum) was purified by preparative GC to obtain the new verticillane diterpenoid verticilla-4(20),7,11-triene (**1403h**), with its relative stereostructure elucidated by 2D-NMR (COSY, HMBC, and NOESY) methods. It is noteworthy that *B. carterii* produces not only verticillane, but also cembrane diterpenoids (105). The same observation was found for the liverwort, *Chandonanthus hirtellus* (422, 423). The Tahitian *C. hirtellus* elaborates not only the cembranes, cembrene (945), cembrene A (946), and chandonanthone (948), but also the *ent*-verticillanes, *ent*-verticillol (1392) and *ent*-12-*epi*-verticillol (1393), which have been isolated from the liverwort *Jackiella javanica*, as mentioned above (423, 494). This represents the second report of the isolation of *ent*-verticillanes from the Marchantiophyta.

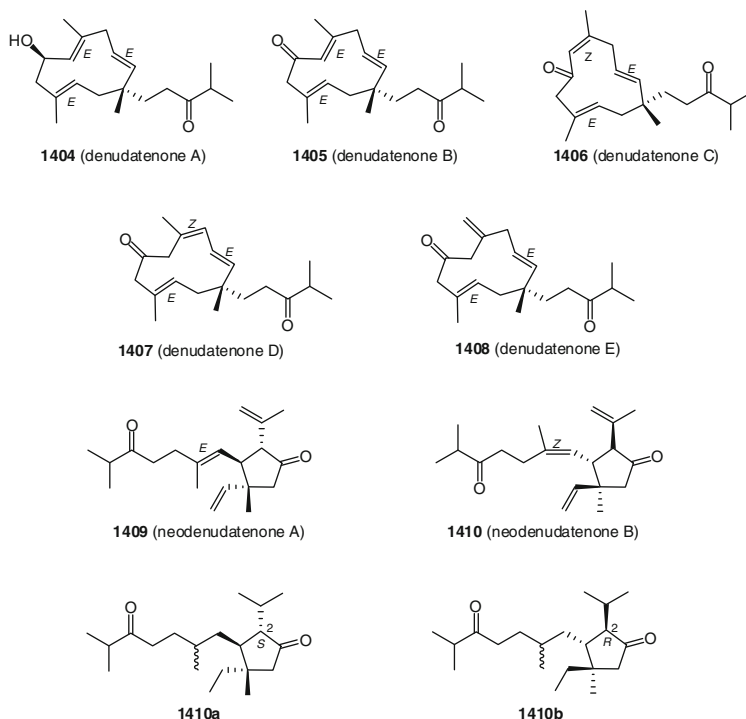


Verticillane-type diterpenoids found in the higher plant, *Bursera suntui*

4.3.16 Vibsanes

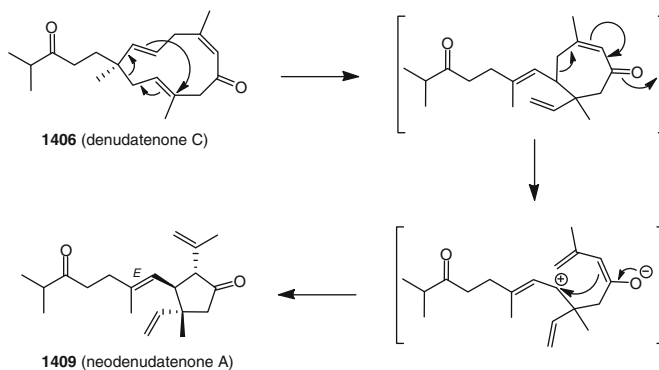
The ether extract of the Japanese *Odontoschisma denudatum* was purified by CC and HPLC to afford the new *ent*-vibsanes, denudatenones A (**1404**), B (**1405**), and C (**1406**), of which **1405** was the major component. The absolute configuration of **1404** was established using a combination of X-ray crystallographic analysis, the modified Mosher's method performed on its MTPA ester, and the negative Cotton effect at 251 nm and the positive optimum at 212 nm of its 3,5-dinitrobenzoate. Denudatenone B (**1405**) is the dihydro derivative of **1404**. In fact, Swern oxidation

of **1404** gave **1405** in good yield. The higher field chemical shift at H-7 of **1406** compared with that of denudatenone B (**1405**) in the ^1H NMR spectrum as well as the analysis of DQF-COSY, HMQC, HMBC, and NOESY experiments readily established the structure of **1406** as the (6,7*Z*)-diastereomer of **1405** ([316](#), [319](#)). These diterpenoids have not yet been found in the other liverworts. Vibsane diterpenes are very rare in Nature. *Fukuyama* and associates reported the isolation and absolute configurations of neovibsanines A and B from the higher plant *Viburnum awabuki* ([237](#), [238](#)). This was the first example of the isolation of *ent*-vibsanines from Nature ([316](#)).

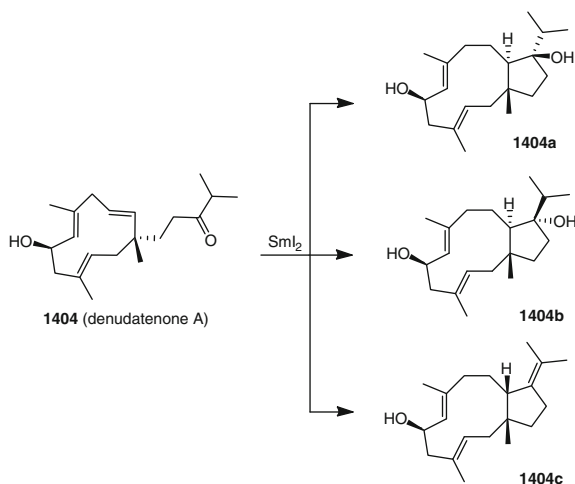


Vibsane- and neodenudatane-type diterpenoids found in the Marchantiophyta and their derivatives

Further fractionation of the ether extract of *Odontoschisma denudatum* led to the isolation of the two new diterpenoids neodenudatenones A (**1409**) and B (**1410**), which possess a new carbon skeleton named the neodenudatane-type. The relative configurations of both these compounds were deduced by 2D-NMR (COSY, HMQC, HMBC, and NOESY) measurements. The absolute configurations of both substances were solved by comparison of the CD spectrum of each compound and their C-10 and C-11 reduced products as well as the signs of their optical rotation (**1410a**: $[\alpha]_{\text{D}} +81^{\circ}\text{cm}^2\text{g}^{-1}\text{10}^{-1}$ **1410b**: $[\alpha]_{\text{D}} -80.1^{\circ}\text{cm}^2\text{g}^{-1}\text{10}^{-1}$). Compound **1409** and its reduced product showed positive *Cotton* effects at 304 and 290 nm, and **1410** and **1410b** displayed negative *Cotton* effects at 302 and 289 nm. Thus, the absolute configurations at C-2 of **1410a** and **1410b** were assigned as (*S*)



Scheme 4.46 Formation of neodenudatanone-type diterpenoid



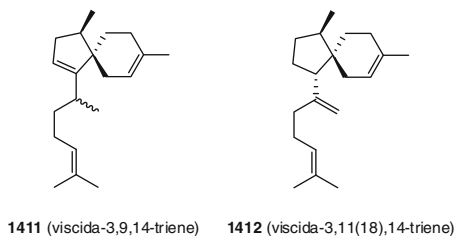
Scheme 4.47 Transformation of vibsane-type diterpenoids to naturally occurring dolabellane-type diterpenoids by samarium diiodide

and (*R*), and consequently the absolute configurations of the natural products **1409** and **1410** were established (317). Neodenudatenones A (**1409**) and B (**1410**), bearing a new carbon skeleton and isolated from the same liverwort, are the first such examples in Nature. It is noteworthy that compounds **1409** and **1410** are enantiomeric except for the diastereomerism of the double bond in the side chain. The neodenudatenones might be formed from denudatenone C (**1406**) by a series of rearrangements, as shown in Scheme 4.46. *Odontoschisma denudatum* produces both vibsane and dolabellane diterpenoids and the biogenesis pathway of both compound types was proposed as shown in Scheme 4.37 (319). Denudatenone A (**1404**) was treated with samarium diiodide in tetrahydrofuran to form the naturally

occurring dolabellane diterpenoid **1404a**, together with its 12-isomer **1404b** and the dehydro product **1404c**, constituting the biogenetic-type transformation of vibsane to dolabellane diterpenoids (Scheme 4.47) (764).

4.3.17 Viscidanes

Radula species are rich sources of bibenzyls and prenyl bibenzyls. The essential oil of the Japanese *Radula perrottetii* was purified by preparative TLC to afford the two new viscidane diterpenoids viscida-3,9,14-triene (**1411**) and viscida-3,11-(18),14-triene (**1412**), for which the structures were determined mainly using HMBC and 2D-NOESY spectra (826). This was the first isolation of viscidane diterpenoid hydrocarbons from the liverworts. Viscidanes have been found in the higher plants, *Eremophila* species (228, 229, 256, 795). The absolute configuration of viscidanes isolated from *Eremophila* species was established as being the same as that of (–)- α -acoradiene (256). Most of the diterpenoids isolated from liverworts are enantiomeric to those found in higher plants. Viscidanes obtained from *Radula* may be expected to be of opposite absolute configuration to those found in the *Eremophila*, although this remains to be clarified.

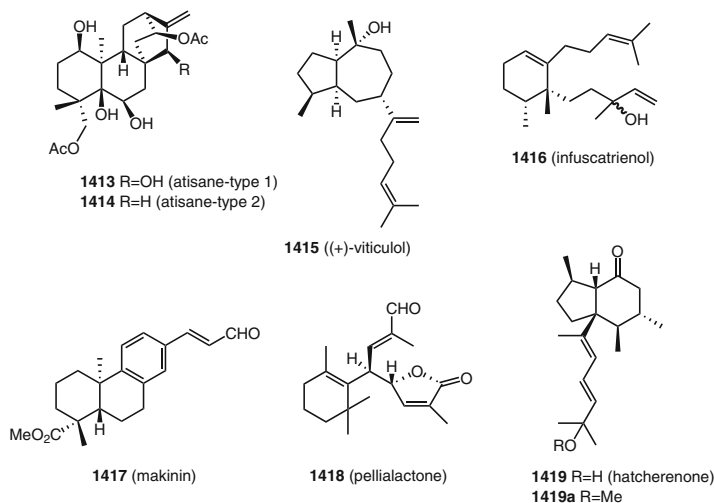


Viscidane-type diterpenoids found in the Marchantiophyta

4.3.18 Miscellaneous

The New Zealand *Lepidolaena clavigera* produces not only oxygenated sesquiterpenes (72) but also the highly oxygenated atisane diterpenoids **1413** and **1414** (655). Their structures were based on the analysis of 2D-NMR spectroscopic data and molecular modeling using PCMODEL (MMX force field).

Reinvestigation of the essential oil of *Saccogyna viticulosa* resulted in the isolation of viticulol (**1415**), a new prenyl-guaiane-type diterpenoid. The global structure containing 10-hydroxyguaian-11,12-ene with an isoprene unit was established by 2D-NMR spectroscopy. The relative configuration was determined by means of a NOESY experiment as (1*R**,4*S**,5*S**,7*S**,10*S**) (276). This was the first isolation of a prenyl-guaiane diterpenoid in the bryophytes. Such compounds have been found mainly in marine algae such as *Dictyota* species.

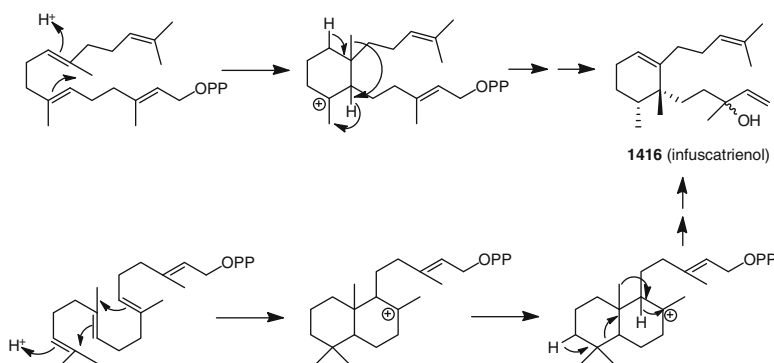


Miscellaneous diterpenoids found in the Marchantiophyta

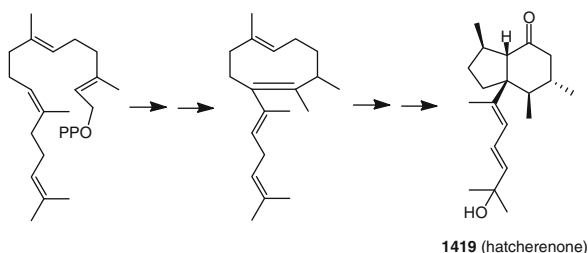
A new monocyclic diterpenoid named infuscatrienol (**1416**) was isolated from the ether extract of the Japanese *Jungermannia infusca*. The structure was assigned by ^1H - ^1H and ^{13}C - ^1H COSY, total correlated spectroscopy (TOCSY), and HMBC as well as NOESY NMR experiments (584, 587). Compound **1416** might be formed from geranylgeranyl pyrophosphate *via* methyl migration and deprotonation (route a), or from a labdane-type intermediate *via* methyl migration, cleavage of a single bond between C-4 and C-5, and deprotonation (route b), as shown in Scheme 4.48 (587).

Makinoa crispata mainly produces the eudesmane sesquiterpene lactone, crispatanolide (**2191**) (40). The same Taiwanese species does not produce lactone **2191**, but a rearranged abietane named makinin (**1417**), for which the structure was assigned as 17(15→16)-*abeo*-abietane by HMBC and NOESY experiments (474). Makinin (**1417**) has not been reported from liverworts previously (40).

The ether extract of the European *Pellia epiphylla* was purified by CC and HPLC to yield the new pellialactone (**1418**) (176). Most *Barbilophozia* species belonging to the Lophoziaceae produce daucane sesquiterpenoids and dolabellane and fusicoccane diterpenoids as the major components. The ether extract of the German *Barbilophozia hatcheri* was fractionated to give a diterpenoid based on a new skeleton named hatcherenone (**1419**). Compound **1419** was converted readily into the methyl ether **1419a** through Sephadex LH-20 column chromatography using the solvent CH_2Cl_2 -MeOH (1:1). The stereostructure of **1419** was based primarily on its 2D-NMR data. The absolute configuration was determined by the application of the back-octant rule to the CD spectrum of **1419a**, which showed a positive Cotton



Scheme 4.48 Possible biogenetic route to infuscatrienol (**1416**) from geranyl-geranyl pyrophosphate



Scheme 4.49 Possible biogenesis pathway for hatcherenane diterpenoids

effect at 295 nm (593). Hatcherenone (**1419**) might be biosynthesized from geranyl-geranyl pyrophosphate *via* a xenicane diterpenoid found in marine organisms, as shown in Scheme 4.49.

4.4 Steroids and Triterpenoids

The phytosterols campesterol (**1420**), stigmasterol (**1421**), and sitosterol (**1426**) have been found in a number of Marchantiophyta species, as shown in Table 4.4.

From the methanol extract of the Japanese *Ricciocarpos natans*, stigmast-4-en-3-one (**1424**) and sitost-4-en-3-one (**1428**) were isolated together with a bibenzyl, lunularic acid, and phytol. This is the first isolation of a steroid ketone from the bryophytes (974). These steroid ketones have been found in some sponges (733) and the heartwood of *Tebebuia rosea* (379). Compound **1424** and stigmast-4-en-3,6-dione (**1425**) were isolated from the Argentinean *Frullania brasiliensis* (98).

Table 4.4 Steroids and triterpenoids found in the Marchantiophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1420	Campesterol	$\text{C}_{28}\text{H}_{48}\text{O}$			<i>Aneura alterniloba</i>	(72)	
					<i>Asterella tenera</i>	(72)	
					<i>Asterella australis</i>	(72)	
					<i>Chiloscyphus triacanthus</i>	(72)	
					<i>Frullania falciloba</i>	(78)	
					<i>Gymnocolea inflata</i>	(882)	
					<i>Isotachis layllii</i>	(73)	
					<i>Jungermannia fusiformis</i>	(876)	
					<i>Kurzia makinoana</i>	(876)	
					<i>Lejeunea parva</i>	(876)	
					<i>Marchantia palmata</i>	(193)	
					<i>Metzgeria furcata</i>	(72)	
					<i>Metzgeria temperata</i>	(882)	
					<i>Pallavicinia levierii</i>	(882)	
					<i>Porella elegantula</i>	(72)	
					<i>Riccardia palmata</i>	(882)	
1421	Stigmasterol	$\text{C}_{29}\text{H}_{48}\text{O}$			<i>Schiffneria hyalina</i>	(882)	
					<i>Schistochila balfouriana</i>	(72)	
					<i>Schistochila repleta</i>	(72)	
					<i>Symphyogyna podophylla</i>	(72)	
					<i>Thysananthus anguliformis</i>	(72)	
					<i>Aneura alterniloba</i>	(72)	
					<i>Apometzgeria pubescens</i>	(882)	
					<i>Barbilophozia floerkei</i>	(583)	
					<i>Chiloscyphus triacanthus</i>	(72)	
					<i>Dumortiera hirsuta</i>	(96)	
						(876)	
					<i>Frullania brasiliensis</i>	(98)	
					<i>Frullania falciloba</i>	(78)	
					<i>Gymnocolea inflata</i>	(882)	
					<i>Isotachis aubertii</i>	(288)	

(continued)

Table 4.4 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
					<i>Isotachis laylii</i>	(73)	
					<i>Jungmannia fusiformis</i>	(882)	
					<i>Kurzia makinoana</i>	(882)	
					<i>Lejeunea parva</i>	(882)	
					<i>Marchantia palmata</i>	(193)	
					<i>Marchantia tosona</i>	(459)	
					<i>Mastigophora dictydos</i>	(287)	
					<i>Metzgeria furcata</i>	(72)	
					<i>Metzgeria temperata</i>	(882)	
					<i>Pallavicinia levierii</i>	(882)	
					<i>Plagiochasma japonica</i>	(459)	
					<i>Plagiochila circinalis</i>	(897)	
					<i>Plagiochasma rupestre</i>	(97)	
					<i>Porella elegantula</i>	(72)	
					<i>Riccardia palmata</i>	(882)	
					<i>Ricciocarpos natans</i>	(974)	
					<i>Scapania undulata</i>	(577)	
					<i>Schiffneria hyalina</i>	(882)	
					<i>Schistochila balfouriana</i>	(72)	
					<i>Schistochila glaucescens</i>	(72)	
					<i>Schistochila nobilis</i>	(607)	
					<i>Schistochila repleta</i>	(635)	
					<i>Symphyogyna podophylla</i>	(72)	
					<i>Thysananthus anguiformis</i>	(72)	
					<i>Trichocolea lanata</i>	(72)	
					<i>Plagiochila circinalis</i>	(898)	
					<i>Frullania hamatiloba</i>	(316)	
					<i>Plagiochasma intermedium</i>	(924)	
					<i>Frullania brasiliensis</i>	(98)	
					<i>Pellia epiphylla</i>	(176)	
					<i>Ricciocarpos natans</i>	(974)	
1422	Stigmasteryl γ -linolenate	$\text{C}_{50}\text{H}_{80}\text{O}_2$					
1423	Stigmasteryl palmitate	$\text{C}_{45}\text{H}_{78}\text{O}_2$					
1424	Stigmast-4-en-3-one	$\text{C}_{29}\text{H}_{46}\text{O}$					

1425	Stigmast-4-en-3,6-dione	$C_{29}H_{44}O_2$	<i>Frullania brasiliensis</i>	(98)
1426	Sitosterol	$C_{29}H_{50}O$	<i>Aneura alterniloba</i>	(72)
			<i>Apometzgeria pubescens</i>	(882)
			<i>Dumortiera hirsuta</i>	(876)
			<i>Frullania brasiliensis</i>	(98)
			<i>Frullania falciloba</i>	(78)
			<i>Gymnocolea inflata</i>	(882)
			<i>Jungermannia fusiformis</i>	(882)
			<i>Jungermannia subulata</i>	(629)
			<i>Kurzia makinoana</i>	(882)
			<i>Lejeunea parva</i>	(882)
			<i>Marchantia palmata</i>	(193)
			<i>Metzgeria furcata</i>	(72)
			<i>Metzgeria temperata</i>	(882)
			<i>Pallavicinia levierii</i>	(882)
			<i>Pellia epiphylla</i>	(176)
			<i>Plagiochasma intermedium</i>	(924)
			<i>Porella elegantula</i>	(72)
			<i>Riccardia palmata</i>	(882)
			<i>Ricciocarpos natans</i>	(974)
			<i>Schiffneria hyalina</i>	(882)
			<i>Schistochila glaucescens</i>	(72)
			<i>Schistochila reptata</i>	(72)
			<i>Symphyogyna podophylla</i>	(72)
			<i>Plagiochasma intermedium</i>	(924)
1427	Daucosterol (=Sitosterol-3-O- β -D-glucopyranoside)	$C_{33}H_{60}O_6$	<i>Ricciocarpos natans</i>	(974)
1428	Sitost-4-en-3-one	$C_{29}H_{48}O$	<i>Pellia epiphylla</i>	(176)
1429	23-Methylcholest-4-en-3-one	$C_{28}H_{46}O$	<i>Pellia epiphylla</i>	(176)
1430	5 α ,8 α -Epidioxy-methylcholesta-6,22-dien-3 β -ol	$C_{28}H_{44}O_3$	<i>Odontoschisma denudatum</i>	(316)
1431	5 α ,8 α -Epidioxy-methylcholesta-6,9(11),22-trien-3 β -ol	$C_{28}H_{42}O_3$	<i>Pellia epiphylla</i>	(176)
			<i>Odontoschisma denudatum</i>	(316)

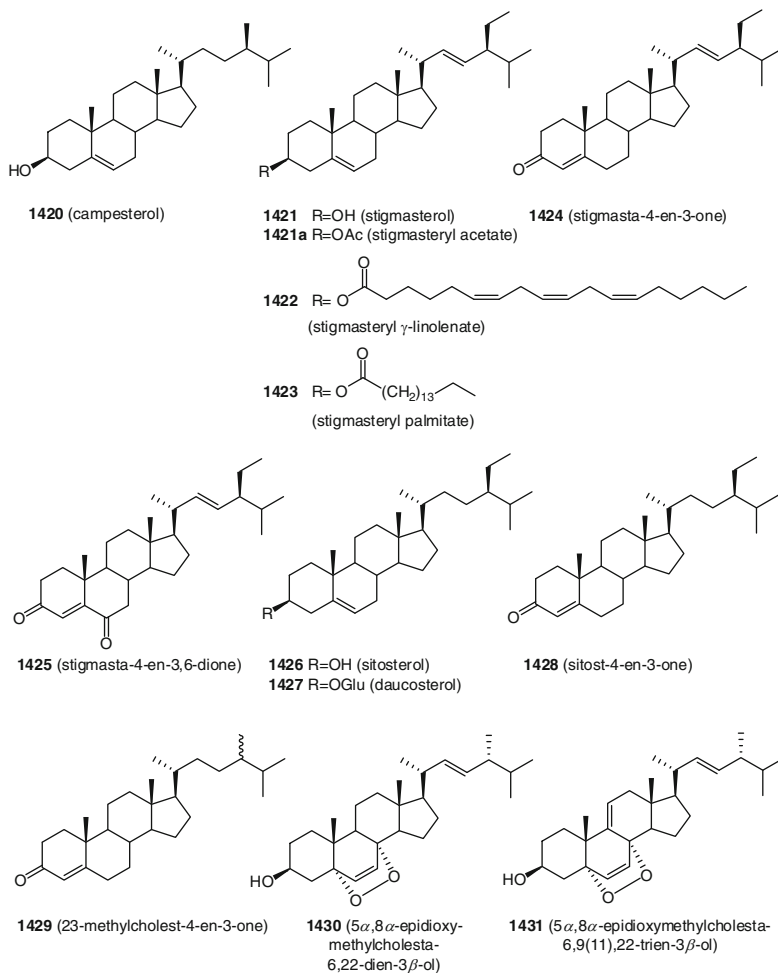
(continued)

1438	Hopan-22,29-diol	C ₃₀ H ₅₂ O ₂	231-233	-6.5	<i>Asterella blumeana</i>	(619)	<i>in vitro</i> Cultures
1439	Methyl 22-hydroxyhopan-29-oate	C ₃₁ H ₅₂ O ₃	212	+43.1	<i>Conocephalum japonicum</i>	(84)	
1440	20-Hydroxy-22(29)-hopene	C ₃₀ H ₅₀ O	215	+37.7	<i>Fossombronina alaskana</i>	(268)	<i>in vitro</i> Cultures
1441	22(30)-Hopan-29-oic acid	C ₃₀ H ₄₈ O ₂	230	+28.9	<i>Fossombronina pusilla</i>	(268)	<i>in vitro</i> Cultures
1442	Adiantone (=30- <i>nor</i> -21 β -Hopan-22-one)	C ₂₉ H ₄₈ O	220-223	+80	<i>Fossombronina alaskana</i>	(268)	<i>in vitro</i> Cultures
1443	Betulin	C ₃₀ H ₅₀ O ₂			<i>Plagioclasma rupestre</i>	(97)	<i>in vitro</i> Cultures
1444	Betulinic acid	C ₃₀ H ₄₈ O ₃			<i>Fossombronina alaskana</i>	(268)	<i>in vitro</i> Cultures
1445	Methyl betulinate	C ₃₁ H ₅₀ O ₃			<i>Pellia epiphylla</i>	(176)	
1446	<i>epi</i> -Betulinic acid	C ₃₀ H ₄₈ O ₃			<i>Heteroscyphus coalitus</i>	(617)	
1447	Tetrahymanol (=21 α -Hydroxygammacerane)	C ₃₀ H ₅₂ O	312	+93.7	<i>Ptilidium pulcherrimum</i>	(271)	
1448	Taraxerol	C ₃₀ H ₅₀ O			<i>Plagioclasma deltoidea</i>	(607)	<i>in vitro</i> Cultures
1449	Taraxerone	C ₃₀ H ₄₈ O			<i>Frullania falciloba</i>	(84)	<i>in vitro</i> Cultures
1450	Friedelin	C ₃₀ H ₅₀ O			<i>Frullania squarrosula</i>	(84)	
1451	3,4- <i>sec-o</i> -Lupa-4(23),20(29)-dien-3,28-dicarboxylic acid dimethyl ester	C ₃₂ H ₅₀ O ₄		+10.3	<i>Fossombronina alaskana</i>	(268)	<i>in vitro</i> Cultures
1452	Cycloartenol	C ₃₀ H ₅₀ O			<i>Fossombronina pusilla</i>	(268)	<i>in vitro</i> Cultures
1453	Cycloart-24-en-3 β -yl linolate	C ₅₀ H ₈₀ O ₂			<i>Frullania fugax</i>	(78)	
1454	Cycloart-24-en-3 β -yl α -linolenate	C ₄₈ H ₇₈ O ₂			<i>Ptilidium pulcherrimum</i>	(271)	
1455	Cycloart-24-en-3-yl 11,14-octadecadienoate	C ₅₀ H ₈₀ O ₂			<i>Ptilidium pulcherrimum</i>	(271)	
					<i>Chandonanthus hirtellus</i>	(927)	
					<i>Jungermannia subulata</i>	(629)	
					<i>Adelanthus lindenbergianus</i>	(116)	
					<i>Herbertus aduncus</i>	(137)	
					<i>Herbertus aduncus</i> subsp. <i>hutchinsia</i>	(137)	
					<i>Herbertus aduncus</i> subsp. <i>hutchinsia</i>	(137)	
					<i>Plagioclasma circinalis</i>	(898)	
					<i>Mastigophora dictados</i>	(287)	

(continued)

Table 4.4 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1456	Cycloart-24-en-3 β -yl arachidonate	C ₅₀ H ₇₈ O ₂			<i>Herbertus aduncus</i> subsp. <i>hutchinsia</i>	(137)	
1457	Cycloart-24-en-3 β -yl eicosapentaenoate	C ₅₀ H ₇₈ O ₂			<i>Plagiochila circinalis</i> <i>Herbertus aduncus</i> subsp. <i>hutchinsia</i>	(898) (137)	
1458	Cycloart-24-en-3 β -yl isostearate	C ₄₈ H ₈₄ O ₂			<i>Mastigophora diclados</i> <i>Plagiochila circinalis</i>	(287) (898)	
1459	Cycloart-24-en-3 β -yl palmitate	C ₄₆ H ₈₀ O ₂			<i>Herbertus aduncus</i> subsp. <i>hutchinsia</i> <i>Herbertus aduncus</i> subsp. <i>hutchinsia</i>	(137) (137)	
1460	21 α -Methoxysearrat-14-en-3-one	C ₃₁ H ₅₀ O ₂			<i>Plagiochila asplenoides</i>	(604)	
1461	Methyl 3 α -hydroxyolean-18-ene-28-oate	C ₃₁ H ₅₀ O ₃	240-242	+15.2	Unidentified <i>Frullania</i> sp.	(843)	
1462	Cycloart-23-en-3 β ,25-diol	C ₃₀ H ₅₀ O ₂			<i>Dendromastigophora flagellifera</i>	(635)	
1463	Cycloart-25-en-3 β ,24 ξ -diol	C ₃₀ H ₅₀ O ₂			<i>Dendromastigophora flagellifera</i>	(635)	
1464	Diospyrolide	C ₂₇ H ₄₂ O ₃			<i>Ptilidium pulcherrimum</i>	(271)	
1465	Diospyrolide acetate	C ₂₉ H ₄₄ O ₄			<i>Ptilidium pulcherrimum</i>	(271)	
1466	3 β -Hydroxy-30-nor-20-oxo-28-lupanoic acid	C ₂₉ H ₄₆ O ₄		+36.1	<i>Ptilidium pulcherrimum</i>	(271)	
1467	Ursolic acid (=3 β -Hydroxyurs-12-en-28-oic acid)	C ₃₀ H ₄₈ O ₃			<i>Ptilidium pulcherrimum</i>	(271)	
1468	Acetoxy ursolic acid	C ₃₂ H ₅₀ O ₄			<i>Ptilidium pulcherrimum</i>	(271)	
1469	2 α ,3 β -Dihydroxyurs-12-en-28-oic acid	C ₃₀ H ₄₈ O ₄			<i>Ptilidium pulcherrimum</i>	(271)	
1470	Ursonic acid (=3-Oxours-12-en-28-oic acid)	C ₃₀ H ₄₆ O ₃			<i>Ptilidium pulcherrimum</i>	(271)	
1471	3 β -Acetoxyurs-11-en-28,13-olide	C ₃₂ H ₄₈ O ₄			<i>Ptilidium pulcherrimum</i>	(271)	



Steroids found in the Marchantiophyta

Daucosterol (= sitosterol-3-*O*- β -D-glucopyranoside) (**1427**) and stigmasteryl palmitate (**1423**) have been purified from *Plagiochasma intermedium* (924). Compound **1423** has also been found in *Frullania hamatiloba* (316).

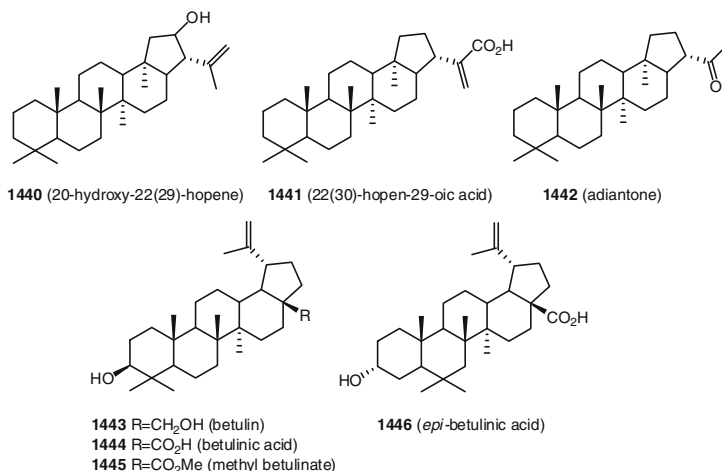
5 α ,8 α -Epidioxymethylcholesta-6,22-dien-3 β -ol (**1430**) and 5 α ,8 α -epidioxymethylcholesta-6,9(11),22-trien-3 β -ol (**1431**) were isolated from the ether extract of *Odontoschisma denudatum* (316) and the European *Pellia epiphylla* (176). The latter species also contains stigmast-4-en-3-one (**1424**) (176).

The isoprene units of stigmasteryl acetate (**1421a**) were shown to be constructed *via* the mevalonic acid (MVA) pathway by an incorporation experiment of ^{13}C labeled glucose into stigmasteryl isolated from *Trichocolea tomentella* (99). Itoh *et al.* also examined the biosynthesis pathway of stigmasteryl (**1421**) using ^{13}C -labeled serines ([1- ^{13}C]- and [3- ^{13}C]-) in the cultured cells of the liverwort, *Heteroscyphus planus*. The labeling pattern in the isoprenoid unit of the ^{13}C -labeled stigmasteryl corresponded to those expected from the MVA pathway (366).

Compound **1436** has been isolated from the liverworts, *Fossombronina alaskana*, *F. pusilla* (268), and *Conocephalum japonicum* (84). The latter liverwort elaborates also hopan-22,29-diol (**1438**). This is the first example of the isolation of **1438** from a natural source. Compound **1438** has been synthesized (243).

From *in vitro*-cultures of *Asterella blumeana*, the three triterpenoids diplopterol (**1436**), hopan-22,29-diol (**1438**), and hopan-6 α ,22-diol (α -zeorin) (**1437**) were isolated and their structures elucidated by spectroscopic methods (619). The New Zealand *Asterella tenera* is chemically quite different from *A. australis* because it contains diploptene (**1435**) (72), which has also been isolated from *Adelanthus lindenbergianus* and a few *Plagiochila* species (40), along with diplopterol (**1436**). The latter compound has been detected in *Conocephalum conicum* and *C. japonicum* (40).

The three new triterpenoids, methyl 22-hydroxyhopan-29-oate (**1439**), 20-hydroxy-22(29)-hopene (**1440**), and 22(30)-hopen-29-oic acid (**1441**) were isolated from *in vitro*-cultured gametophytes of an Arctic *Fossombronina alaskana*, along with the known related hopanoids, adiantone (**1442**), diplopterol (**1436**), and tetrahymanol (= 21 α -hydroxygammacerane) (**1447**) (268). The structure of **1439** was deduced by comparison of its NMR data with those of diplopterol (**1436**). The structure of the second triterpene **1440** was, in turn, based on comparison of spectroscopic data with **1439** and **1442**. The NMR spectrum of **1441** showed signals for a vinylic methylene and a carboxylic acid in place of the methyl vinyl group present in **1440**. Thus, the structure of **1441** was confirmed. Compounds **1436**, **1439**, **1441**, and **1447** were also isolated from *F. alaskana* gametophytes. Two of the same triterpenes (**1439** and **1441**) were isolated from *Fossombronina pusilla* (268). This was the first report on the chemical constituents of *F. alaskana*.

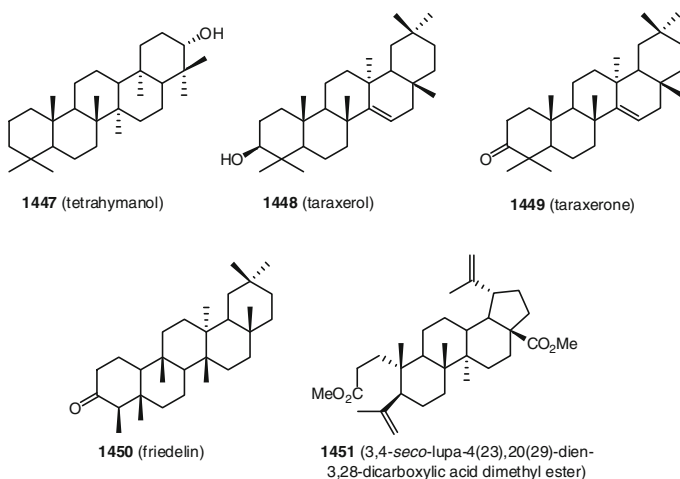


Triterpenoids found in the Marchantiophyta

The incorporation of glucose in 22(30)-hopen-29-oic acid (**1441**) was studied by feeding [^{13}C] labeled glucose into axenic cultures of the Arctic *Fossombronia alaskana*. Quantitative ^{13}C NMR spectroscopic analysis of the resulting labeled profiles indicated that the isoprene units of **1441** are constructed *via* the methyl-erythrol phosphate pathway (339).

Adiantone (= 20-*nor*-21 β -hopan-22-one) (**1442**) and diplopterol (**1436**) were found in the Argentinean *Plagiochasma rupestre* (97).

The ether extract of the European *Pellia epiphylla* was purified by CC and HPLC to yield betulin (**1443**) (176). Betulinic acid (**1444**) was identified in *Heteroscyphus* (617) and *Ptilidium* species (271). The ether extracts of the New Zealand *Frullania falciloba* and *F. squarrosula* were fractionated to give *epi*-betulinic acid (**1446**) (84). The New Zealand collection of *Plagiochila deltoidea* gave betulinic acid methyl ester (**1445**) (607).



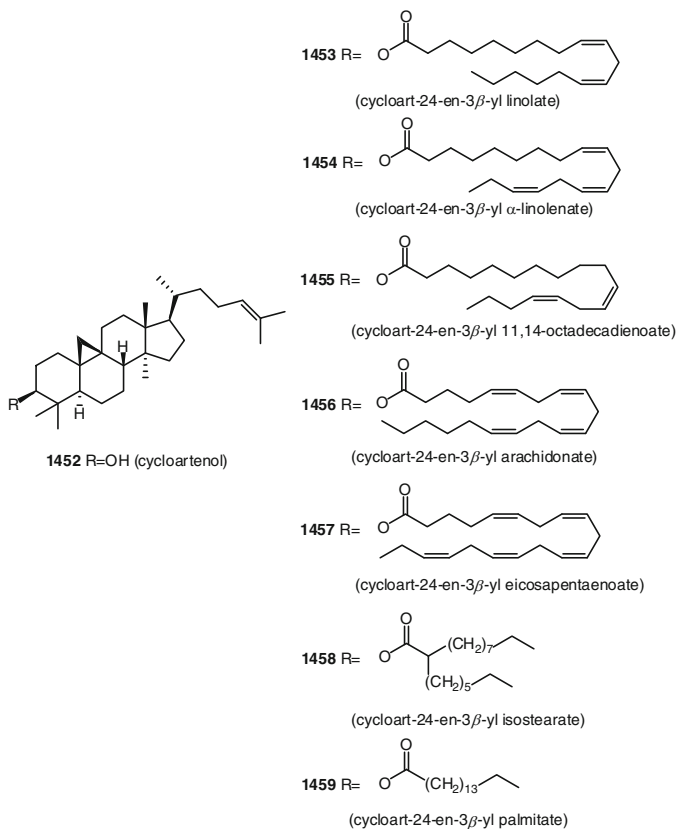
Triterpenoids found in the Marchantiophyta

Only one species so far, *Jungermannia sublata*, has been found to produce friedelin (**1450**) (629). The methanol extract of the Patagonian *Adelanthus lindenbergianus* contained the 3,4-secolupane triterpene, **1451** (116). The NMR spectra of this substance resembled those of canaric acid, a 3,4-cleaved lupane-3,28-dioic acid 3-methyl ester (185). The compound contained two methyl ester groups. Thus, the structure of **1451** was determined as 3,4-*seco*-lupa-4(23),20(29)-dien-3,28-dicarboxylic acid dimethyl ester.

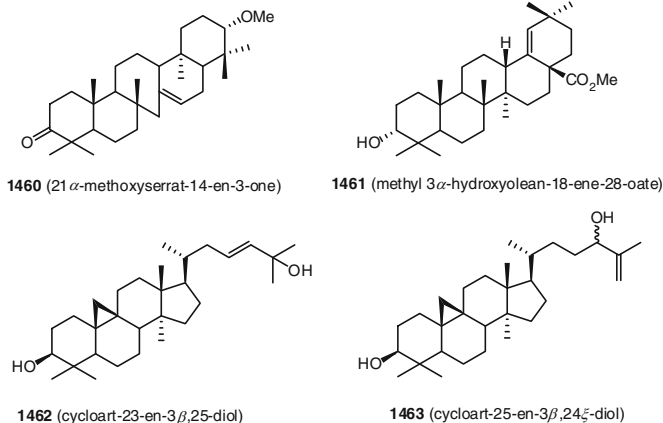
Buchanan and coworkers confirmed the presence of cycloartenol (**1452**) and a mixture of cycloartenyl linolate (**1453**), α -linolenate (**1454**), arachidonate (**1456**), eicosa-(5*Z*,8*Z*,11*Z*,14*Z*,17*Z*)-pentaenoate (**1457**), isostearate (**1458**), and hexadecanoate (**1459**) in *Herbertus aduncus* subsp. *hutchinsiae*. Their structures

were assigned by methanolysis of the mixture to produce cycloartenol (**1452**) and fatty acid methyl esters of linoleic, α -linolenic, arachidonic, eicosa-(5Z,8Z,11Z,14Z,17Z)-pentaenoic, hexadecanoic, and isostearic acids, which were confirmed by GC/MS (**137**).

From the New Zealand *Plagiochila circinalis*, a mixture of cycloartenyl esters was obtained. Hydrolysis of the esters gave cycloartenol (**1452**) and a series of fatty acids, which were esterified with trimethylsilyldiazomethane to give several fatty acid methyl esters. GC/MS analysis was performed to identify methyl α -linolenate, methyl arachidonate, and methyl eicosapentaenoate. On the basis of the above chemical reactions and the molecular ion peaks in the HRMS of the mixtures, it became clear that *P. circinalis* biosynthesizes cycloarta-24-en-3 β -yl α -linolenate (**1454**), cycloarta-24-en-3 β -yl arachidonate (**1456**), and cycloarta-24-en-3 β -yl eicosapentaenoate (**1457**) (**84**, **898**).



Triterpenoids found in the Marchantiophyta



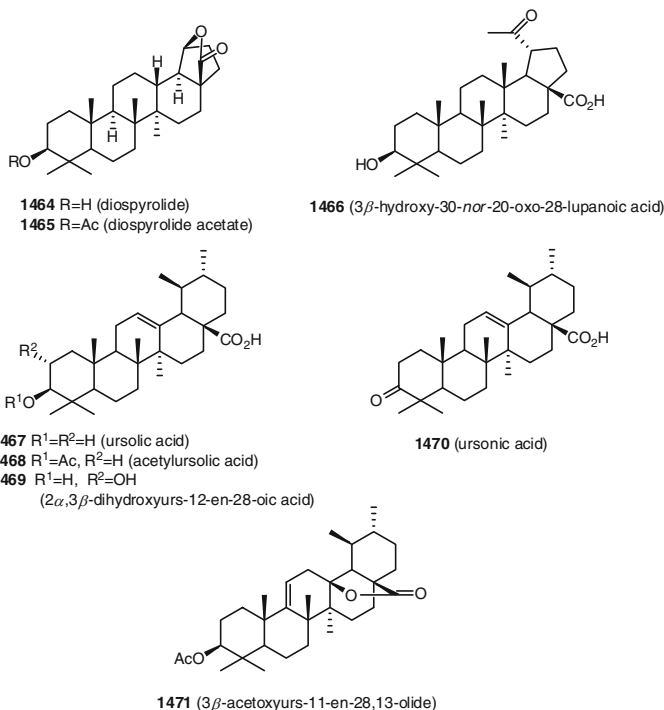
Triterpenoids found in the Marchantiophyta

The ether extract of the Madagascan *Mastigophora diclados* was fractionated by size-exclusion chromatography to give a mixture of the cycloartenyl esters **1455** and **1457**, which were saponified to give cycloartenol (**1452**), eicosapentaenoic acid (**2026**), and 11,14-octadecadienoic acid (**2016**) (**287**).

The ether extract of the European *Plagiochila asplenioides* was investigated further to afford 21 α -methoxyserrat-14-en-3-one (**1460**) (**604**), which has been found in the liverwort *Nardia* species as an artifact (**40**).

The ether extract of an unidentified Venezuelan *Frullania* species was purified by CC and preparative TLC to give a new pentacyclic triterpene, with its structure deduced by means of HMBC correlations as methyl 3 α -hydroxyolean-18-en-28-oate (**1461**). Its configuration was determined using a NOESY experiment. This was the first report of an oleanane triterpene from the liverworts (**843**). Fractionation of the ether extract of the New Zealand *Dendromastigophora flagellifera* led to the isolation of the known triterpene alcohols cycloart-25-en-3 β ,24 ξ -diol (**1463**) and cycloart-23-en-3 β ,25-diol (**1462**) (**635**).

The Chinese *Ptilidium pucherrimum*, when collected on a mountain (4,000 m altitude), produced diospyrolide (**1464**) and diospyrolide acetate (**1465**) together with 3 β -hydroxy-30-nor-20-oxo-28-lupanoic acid (**1466**), betulinic acid (**1444**), taraxerol (**1448**), taraxerone (**1449**), ursolic acid (**1467**), ursonic acid (**1470**), 2 α ,3 β -dihydroxyurs-12-en-28-oic acid (**1469**), acetylursolic acid (**1468**), and 3 β -acetoxyurs-11-en-28,13-olide (**1471**) (**271**).



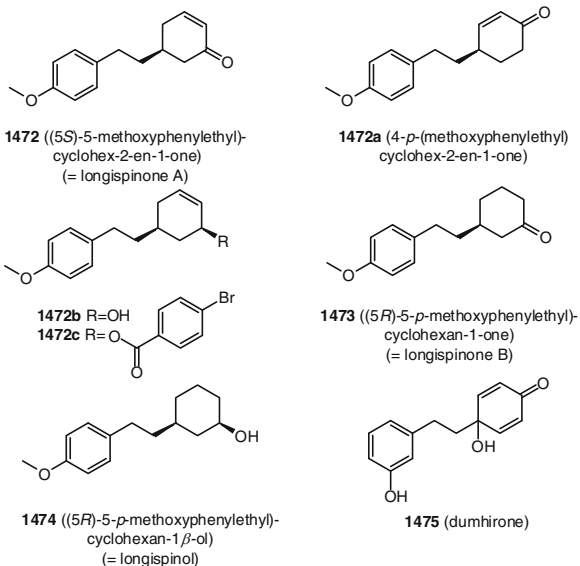
Triterpenoids found in the Marchantiophyta

4.5 Aromatic Compounds

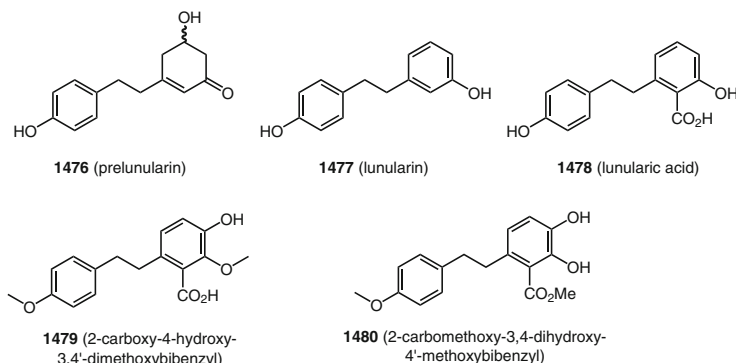
The most characteristic compounds in the Marchantiophyta are bis-bibenzylys, which have been found not only in Jungermanniales and Marchantiales but also the Metzgeriales. In particular, *Marchantia* species are rich source of bis-bibenzylys. The dimeric bis-bibenzylys are characteristic components in *Riccardia* and *Blasia* species. The presence of various types of bibenzylys and their derivatives, benzylphthalides, phenanthrenes and their dihydro analogues, have been isolated from many different liverwort species. The genus *Radula* is a rich source of bibenzylys and prenyl bibenzylys. Methyl benzoates with prenyl groups are very important chemical markers of *Trichocolea* species. The presence of nitrogen-sulfur-containing compounds is restricted presently to *Corsinia coriandrina*.

4.5.1 Bibenzyls

Liverworts are abundant sources of bibenzyl and prenyl bibenzyls (39, 40). Several new bibenzyls have been found in the Jungermanniales, Metzgeriales, and Marchantiales, together with a number of known bibenzyls. Among them, lunularin (1477), lunularic acid (1478), 3-methoxy-4'-hydroxybibenzyl (1482), 3-hydroxy-4'-methoxybibenzyl (1483), 3-methoxy-3',4'-methylenedioxybibenzyl (1487), 3-methoxybibenzyl (1493), 3,4'-dimethoxybibenzyl (1501), 2,2-dimethoxy-5-hydroxy-7-(2-phenylethyl)chromene (1509), radulanins A (1511) and J (1515), 3,5-dihydroxy-2-(3-methyl-2-butenyl) bibenzyl (1525), 2-geranyl-3,5-dihydroxybibenzyl (1530), and (2*S*)-2-methyl-2-(4-methyl-3-phenyl)-7-hydroxy-5-(2-phenylethyl)chromene (= *o*-cannabichromene) (1534) are relatively common bibenzyls. The bibenzyls and prenyl bibenzyls have been found mainly in *Frullania*, *Plagiochila*, and *Radula* species belonging to the Jungermanniales.



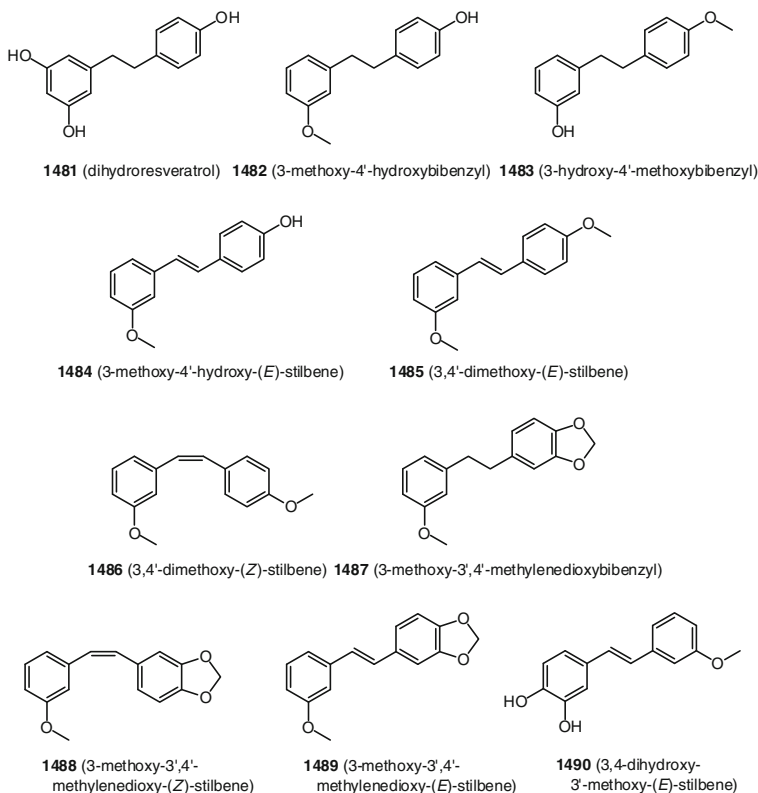
Prebibenzyls found in the Marchantiophyta and a bromo derivative



A prebibenzyl and bibenzyls found in the Marchantiophyta

Several *Radula* species collected in Japan, Germany, New Zealand, Peru, and Saudi Arabia were analyzed chemically and thereby it was confirmed that the most widely distributed components among these species are 3,5-dihydroxy-2-(3-methyl-2-butenyl)-bibenzyl (**1525**) and 2-geranyl-3,5-dihydroxybibenzyl (**1530**) (82).

Heinrichs and coworkers reported that *Plagiochila buchtiniana*, *P. diversifolia*, and *P. longispina*, produce the three prebibenzyls, longispinone A (**1472**), longispinone B (**1473**), and longispinol (**1474**) (330). However, their spectroscopic data have not been reported. *Balantiopsis rosea* is known to elaborate a sulfur-containing acrylate, a phthalide, and methyl benzoate (40). Further fractionation of the ether extract of the New Zealand *Balantiopsis rosea* resulted in the isolation of the same three prebibenzyls **1472–1474**, as mentioned above. Their absolute stereostructures were determined to be (5*S*)-*p*-(methoxyphenylethyl)cyclohexan-1-one (**1472**), (5*R*)-*p*-(methoxyphenylethyl)cyclohexan-1-ol (**1473**), and (5*R*)-*p*-(methoxyphenylethyl)cyclohex-2-en-1-one (**1474**) (612). The spectroscopic data of **1472** were not identical to those of 4-*p*-(methoxyphenylethyl)cyclohex-2-en-1-one (**1472a**) isolated from *Plagiochila longispina* (40), indicating that **1472** is an isomer of **1472a**. Detailed analysis of the NOESY spectrum of the monoalcohol **1472b** prepared from **1472** led to the structure of the latter compound. The absolute configuration was settled by the application of the allyl benzoate rule to the CD spectrum of the *p*-bromobenzoate **1472c** prepared from **1472b**. The structural determination of **1473** was based on a combination of a detailed analysis of the 1D- and 2D-NMR spectroscopic data. Its absolute configuration was established from the observation of a negative *Cotton* effect at 293 nm and a positive *Cotton* effect at 223 nm. The structure of **1474** was established by a combination of 2D-NMR spectroscopic data interpretation and by a chemical reaction and X-ray crystallography. Reduction of **1473** with LiAlH_4 gave two monoalcohols, of which one proved to be identical to **1474**. The absolute configuration of **1474** was confirmed by its X-ray crystallographic analysis and from the similar *Cotton* effects seen for compound **1473** (612).



Bibenzyls and stilbenoids found in the Marchantiophyta

Compounds **1472–1474**, which are probable precursors of the dicarboxylic bibenzyls, 3-hydroxy-4'-methoxybibenzyl (**1483**) and 3,4'-dimethoxybibenzyl (**1501**), or the cyclic bis-bibenzyls marchantin A (**1577**), perrottetin E (**1636**), and riccardin A (**1564**), found in the liverworts *Frullania*, *Plagiochila*, *Radula*, *Marchantia*, and *Riccardia* species (40), were isolated for the first time from a liverwort. Two similar *p*-substituted phenylethyl cyclohexane derivatives, **1472a** and **1476**, are known in the liverworts *Plagiochila longispina* and *Marchantia polymorpha* (40).

Dumortiera hirsuta produces not only sesquiterpenoids but also bis-bibenzyls (40). Xie *et al.* found that a Chinese specimen produced dumhirone A (**1475**), an unusual phenylethyl cyclohexadienone, and its structure was elucidated by analysis of its 2D-NMR spectroscopic data (966). The same compound was identified in the volatile components of *Dumortiera hirsuta* collected in Borneo (490).

Prelunularin (**1476**), which was previously obtained from *Marchantia polymorpha* (40), was isolated from *Ricciocarpos natans* (453) and *Conocephalum conicum* (type I) (880). Comas and Pandolf achieved the first total synthesis of racemic prelunularin (**1476**) in eight steps with 9% overall yield from (3*E*)-6-[(4-*tert*-butyldimethylsilyloxy)phenyl]hex-3-en-2-one (158).

Lunularin (**1477**) and lunularic acid (**1478**) had been identified in 77 species of liverworts, as of 1995 (39, 40). The Tahitian *Cyathodium foetidissimum* has a very strong unpleasant odor when it is crushed. GC/MS analysis of its ether extract indicated the presence of lunularin (**1477**) (494). Compound **1477** was further detected in *Blasia pusilla*, *Frullania convoluta*, *Marchantia tosona*, and *Monoclea forsteri*, with **1478** found in the first two of these species and in *Ricciocarpos natans*, as shown in Table 4.5. Compound **1477** was isolated from the methanol extract of sterile cultures of *Marchantia polymorpha* (8).

From the dichloromethane extract of an unidentified Costa Rican *Plagiochila* species, Anton and colleagues isolated a new bibenzyl, for which the structure was characterized as 2-carboxy-4-hydroxy-3,4'-dimethoxybibenzyl (**1479**) by analysis of the HMQC, HMBC, and NOESY data (33). Also obtained in the same investigation were the known bibenzyls, 3-methoxy-4'-hydroxybibenzyl (**1482**), 3,4'-dimethoxybibenzyl (**1501**), 3,5-dihydroxy-2-(3-methyl-2-butenyl)bibenzyl (**1525**), and 2,2-dimethyl-7-hydroxy-5-(2-phenylethyl)chromene (**1507**) (33, 40).

Connolly and associates reported that the British *Plagiochila spinulosa* produces not only dihydrophenanthrenes and methyl benzoate derivatives (40), but also 2-carbomethoxy-3,4-dihydroxy-4'-methoxybibenzyl (**1480**), of which the structure was elucidated by 2D-NMR data, especially using the HMBC spectrum (165). The same bibenzyl was also identified in *P. bifaria* (333) and *P. retrorsa* (698).

Dihydroresveratol (**1481**), which has been isolated from the tubers of the yam, *Dioscorea dumentorum* (Dioscoreaceae) (13), was isolated also from *Blasia pusilla* belonging to the Metzgeriales (971). 3-Hydroxy-4'-methoxybibenzyl (**1483**) has been detected in *Frullania davurica* (40). This same compound was identified in one additional *Frullania* species and five *Plagiochila* species, as shown in Table 4.5. GC/MS analysis of the New Zealand *Marsupidium perpusillum* showed the presence of 3-methoxy-4'-hydroxybibenzyl (**1482**) and 3-methoxy-4'-hydroxy-(*E*)-stilbene (**1484**) as the major components. This species was found to produce 3-hydroxybibenzyl (**1492**) and 3-methoxybibenzyl (**1493**) as minor components (40, 72).

Flegel and Becker analyzed the oil bodies of *Radula complanata* by GC/MS and confirmed that it contains 3-methoxybibenzyl (**1493**) as a major component (227). The Mediterranean liverwort *Corsinia coriandrina* produces 3,4'-dimethoxy-(*E*)-stilbene (**1485**) and 3,4'-dimethoxy-(*Z*)-stilbene (**1486**), together with 3,4'-dimethoxybibenzyl (**1501**) and several 2-arylbenzofurans (**1815–1817**) as minor components (920).

The ether extract of an unidentified Venezuelan *Frullania* species was purified by column chromatography and preparative TLC to give 3-methoxy-3',4'-methylenedioxybibenzyl (**1487**) (843). The same compound was found in six different *Frullania* species (78) and *Trocholejeunea sandvicensis* (460), belonging to the Lejeuneaceae, as shown in Table 4.5. Two stilbenes, 3-methoxy-3',4'-methylenedioxy-(*Z*)-stilbene (**1488**) and 3-methoxy-3',4'-methylenedioxy-(*E*)-stilbene (**1489**), were identified in the ether extract of *Frullania anomala* (78).

The chloroform extract of the neotropical *Marchesinia bongardiana* was purified by column chromatography on Sephadex LH-20 to afford 3,4-dihydroxy-3'-methoxy-(*E*)-stilbene (**1490**) for which the structure was proved by a combination of the analysis of its 2D-NMR data, inclusive of the COSY spectrum, and from its

Table 4.5 Bibenzyls found in the Marchantiophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1472	(5 <i>R</i>)-5- <i>p</i> -(Methoxyphenylethyl)-cyclohex-2-en-1-one (= Longispinone A)	$\text{C}_{15}\text{H}_{18}\text{O}_2$		+18.5	<i>Balantiopsis rosea</i> <i>Plagiochila buchtiniana</i> <i>Plagiochila diversifolia</i> <i>Plagiochila longispina</i> <i>Balantiopsis rosea</i> <i>Plagiochila buchtiniana</i> <i>Plagiochila diversifolia</i> <i>Plagiochila longispina</i>	(612) (330) (330) (330) (612) (330) (330) (330)	
1473	(5 <i>R</i>)-5- <i>p</i> -(Methoxyphenylethyl)-cyclohexan-1-one (= Longispinone B)	$\text{C}_{15}\text{H}_{20}\text{O}_2$		-10.5	<i>Balantiopsis rosea</i> <i>Plagiochila buchtiniana</i> <i>Plagiochila diversifolia</i> <i>Plagiochila longispina</i>	(330) (330) (330) (330)	
1474	(5 <i>S</i>)-5- <i>p</i> -(Methoxyphenylethyl)-cyclohexan-1-β-ol (= Longispinol)	$\text{C}_{15}\text{H}_{22}\text{O}_2$		-10.2	<i>Balantiopsis rosea</i> <i>Plagiochila buchtiniana</i> <i>Plagiochila diversifolia</i> <i>Plagiochila longispina</i> <i>Dumortiera hirsuta</i>	(612) (330) (330) (330) (488)	X-ray
1475	Dumthirone A	$\text{C}_{14}\text{H}_{14}\text{O}_3$				(966)	
1476	Prelunarin	$\text{C}_{14}\text{H}_{16}\text{O}_3$			<i>Conocephalum conicum</i> <i>Ricciocarpos natans</i> <i>Blasia pusilla</i>	(880) (453) (971)	
1477	Lunularin	$\text{C}_{14}\text{H}_{14}\text{O}_2$			<i>Conocephalum conicum</i> <i>Cyathodium foetidissimum</i> <i>Dumortiera hirsuta</i> <i>Frullania convoluta</i> <i>Lunularia cruciata</i> <i>Marchantia tosona</i> <i>Monoclea forsteri</i>	(487) (494) (487) (883) (226) (72) (79) (459) (72)	

1478	Lunularic acid	$C_{15}H_{14}O_4$	<i>Blasia pusilla</i> (971) <i>Frullania convoluta</i> (226) <i>Lunularia cruciata</i> (72) <i>Marchantia polymorpha</i> (8) <i>Ricciocarpos natans</i> (974) <i>Plagiochila permista</i> var. <i>integerrima</i> (33) <i>Plagiochila bifaria</i> (333) <i>Plagiochila retrorsa</i> (698) <i>Plagiochila spinulosa</i> (165) <i>Plagiochila stricta</i> (699) <i>Blasia pusilla</i> (971) <i>Marsupidium perpusillum</i> (72) <i>Plagiochila fasciculata</i> (72) <i>Plagiochila gymnoclycina</i> (700) <i>Plagiochila maderensis</i> (33) <i>Plagiochila permista</i> var. <i>integerrima</i> (72) <i>Plagiochila stephensoniana</i> (482) <i>Plagiochila trichostoma</i> (34) <i>Frullania muscicola</i> (484) <i>Plagiochila buchiniana</i> (330) <i>Plagiochila diversifolia</i> (330) <i>Plagiochila longispina</i> (693) <i>Plagiochila rutilans</i> (693) <i>Plagiochila standleyi</i> (693)	Cell culture	GC-MS
1479	2-Carboxy-4-hydroxy-3,4'-dimethoxy-biphenyl	$C_{17}H_{18}O_5$			
1480	2-Carbomethoxy-3,4-dihydroxy-4'-methoxybiphenyl	$C_{17}H_{18}O_5$			
1481	Dihydroresveratrol				
1482	3-Methoxy-4'-hydroxybiphenyl	$C_{15}H_{16}O_2$			
1483	3-Hydroxy-4'-methoxybiphenyl	$C_{15}H_{16}O_2$			

(continued)

Table 4.5 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1484	3-Methoxy-4'-hydroxy-(<i>E</i>)-stilbene	$\text{C}_{15}\text{H}_{14}\text{O}_2$			<i>Marsupidium perpusillum</i>	(72)	GC-MS
1485	3,4'-Dimethoxy-(<i>E</i>)-stilbene	$\text{C}_{16}\text{H}_{16}$			<i>Corsinia coriandrina</i>	(79) (920)	
1486	3,4'-Dimethoxy-(<i>Z</i>)-stilbene	$\text{C}_{16}\text{H}_{16}$			<i>Corsinia coriandrina</i>	(79) (920)	
1487	3-Methoxy-3',4'-methylenedioxy-bibenzyl	$\text{C}_{16}\text{H}_{16}\text{O}_3$			<i>Frullania anomala</i> <i>Frullania falciloba</i> <i>Frullania incumbens</i> <i>Frullania pycnantha</i> <i>Frullania scandens</i> <i>Frullania spinifera</i> Unidentified <i>Frullania</i> sp.	(78) (78) (72) (78) (78) (78) (843)	GC-MS
1488	3-Methoxy-3',4'-methylenedioxy-(<i>Z</i>)-stilbene	$\text{C}_{16}\text{H}_{14}\text{O}_3$			<i>Trocholejeunea sandvicensis</i>	(424) (460)	
1489	3-Methoxy-3',4'-methylenedioxy-(<i>E</i>)-stilbene	$\text{C}_{16}\text{H}_{14}\text{O}_3$			<i>Frullania anomala</i>	(78)	
1490	3,4-Dihydroxy-3'-methoxy-(<i>E</i>)-stilbene	$\text{C}_{15}\text{H}_{14}\text{O}_3$	102		<i>Frullania anomala</i>	(78)	
1491	2,5-Di- <i>O</i> - β -D-glucopyranosyl-4'-hydroxybibenzyl	$\text{C}_{26}\text{H}_{34}\text{O}_{13}$		-114	<i>Marchesinia bongardiana</i> <i>Marchantia polymorpha</i>	(765) (667)	
1492	3-Hydroxybibenzyl	$\text{C}_{14}\text{H}_{14}\text{O}$			<i>Marsupidium perpusillum</i>	(72)	GC-MS
1493	3-Methoxybibenzyl	$\text{C}_{15}\text{H}_{16}\text{O}$			<i>Marsupidium perpusillum</i> <i>Porella cordaeana</i>	(72) (79)	GC-MS

1494	3,4-Dihydroxy-3'-methoxybibenzyl	C ₁₅ H ₁₆ O ₃	<i>Radula buccinifera</i> <i>Radula complanata</i> <i>Radula lindenbergiana</i> <i>Radula nudicaulis</i> <i>Plagiochila exigua</i> <i>Plagiochila</i> sp. <i>Plagiochila</i> sp. <i>Frullania falciloba</i> <i>Frullania muscicola</i> Unidentified <i>Frullania</i> sp.	(72) (223) (223) (223) (694) (34) (34) (78) (484) (424)
1495	4-Hydroxy-3,3'-dimethoxybibenzyl	C ₁₆ H ₁₈ O ₃		
1496	3-Hydroxy-4,3'-dimethoxybibenzyl	C ₁₆ H ₁₈ O ₃		
1497	4-Hydroxy-3,4'-dimethoxybibenzyl	C ₁₆ H ₁₈ O ₃		
1498	3-Hydroxy-4,3'-dimethoxybibenzyl	C ₁₆ H ₁₈ O ₃	<i>Frullania scandens</i>	(78)
1499	Brittonin B	C ₁₉ H ₂₂ O ₆	<i>Frullania pycnantha</i>	(78)
1500	3,3',4,4'-Dimethylenedioxybibenzyl	C ₁₆ H ₁₄ O ₄	<i>Frullania spinifera</i>	(78)
1501	3,4'-Dimethoxybibenzyl	C ₁₆ H ₁₈ O ₂	<i>Corsinia coriandrina</i> <i>Frullania falciloba</i> <i>Frullania scandens</i> Unidentified <i>Frullania</i> sp.	(79) (78) (78) (424)
1502	3,3',4'-Trimethoxybibenzyl	C ₁₇ H ₂₀ O ₃	<i>Plagiochila diversifolia</i> <i>Plagiochila permista</i> var. <i>integerrima</i> <i>Plagiochila stephensoniana</i> <i>Radula aquilegia</i> <i>Radula buccinifera</i> <i>Radula complanata</i> <i>Radula lindenbergiana</i> <i>Radula nudicaulis</i> <i>Radula wichurae</i> <i>Frullania brasiliensis</i>	(330) (33) (72) (223) (72) (223) (223) (223) (223) (223) (98)

(continued)

Table 4.5 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
					Unidentified <i>Frullania</i> sp.	(424)	
1503	3,5,4'-Trimethoxybibenzyl	$\text{C}_{17}\text{H}_{20}\text{O}_3$			<i>Monoselenium tenerum</i>	(489)	
1504	Pellepiphyllin	$\text{C}_{16}\text{H}_{18}\text{O}_3$			<i>Pellia epiphylla</i>	(182)	
1505	7-Hydroxypellepiphyllin	$\text{C}_{16}\text{H}_{18}\text{O}_4$			<i>Pellia epiphylla</i>	(182)	
1506	Tylimanthin B	$\text{C}_{19}\text{H}_{20}\text{O}_2$			<i>Radula buccinifera</i>	(72)	
1507	2,2-Dimethyl-7-hydroxy-5-(2-phenylethyl)chromene	$\text{C}_{19}\text{H}_{20}\text{O}_2$			<i>Plagiochila permista</i> var. <i>integerrima</i>	(33)	
					Unidentified	(33)	
					<i>Plagiochila</i> sp.		
					<i>Radula buccinifera</i>	(623)	
					<i>Radula boryana</i>	(623)	
					<i>Radula brunea</i>	(623)	
					<i>Radula campanigera</i>	(623)	
					<i>Radula chinensis</i>	(623)	
					<i>Radula javanica</i>	(623)	
					<i>Radula obtusiloba</i>	(623)	
					<i>Radula okamurana</i>	(623)	
					<i>Radula uvifera</i>	(623)	
					<i>Tylimanthus saccatus</i>	(72)	
1508	2,2-Dimethyl-7-methoxy-5-(2-phenylethyl)chromene	$\text{C}_{20}\text{H}_{22}\text{O}_2$			<i>Radula grandis</i>	(623)	
					<i>Radula javanica</i>	(623)	
					<i>Tylimanthus saccatus</i>	(72)	
1509	2,2-Dimethyl-5-hydroxy-7-(2-phenylethyl)chromene	$\text{C}_{19}\text{H}_{20}\text{O}_2$			<i>Radula boryana</i>	(224)	
					<i>Radula buccinifera</i>	(623)	
					<i>Radula carringtonii</i>	(223)	
					<i>Radula kojana</i>	(623)	
					<i>Radula laxiramea</i>	(178)	

1510	2,2-Dimethyl-5-methoxy-7-(2-phenylethyl)chromene	$C_{20}H_{22}O_2$	<i>Radula lindenbergiana</i>	(223)
				(623)
			<i>Radula nudicaulis</i>	(223)
			<i>Radula tokiensis</i>	(623)
			<i>Radula wichurae</i>	(223)
1511	Radulanin A	$C_{19}H_{20}O_2$	<i>Radula obtusiloba</i>	(623)
				(294)
			<i>Radula appressa</i>	(72)
			<i>Radula buccinifera</i>	(623)
			<i>Radula constricta</i>	(72)
1512	Radulanin C	$C_{19}H_{20}O_3$	<i>Radula grandis</i>	(623)
				(623)
			<i>Radula javanica</i>	(623)
			<i>Radula lindenbergiana</i>	(623)
			<i>Radula tokiensis</i>	(623)
1513	Radulanin H	$C_{20}H_{20}O_4$	<i>Radula buccinifera</i>	(72)
				(223)
			<i>Radula lindenbergiana</i>	(623)
			<i>Radula constricta</i>	(72)
			<i>Radula grandis</i>	(623)
1514	Radulanin I	$C_{19}H_{20}O_2$		(623)
			<i>Radula javanica</i>	(623)
			<i>Radula lindenbergiana</i>	(623)
			<i>Radula obtusiloba</i>	(623)
			<i>Radula okamuraana</i>	(623)
1515	Radulanin J	$C_{20}H_{22}O_2$	<i>Radula tokiensis</i>	(623)
				(72)
			<i>Radula uvifera</i>	(623)
			<i>Radula constricta</i>	(72)
			<i>Radula grandis</i>	(623)
1516	Radulanin K	$C_{20}H_{22}O_2$	<i>Radula obtusiloba</i>	(623)
			<i>Radula okamuraana</i>	(623)
			<i>Radula tokiensis</i>	(623)

(continued)

Table 4.5 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1516	Radulanin L	$\text{C}_{19}\text{H}_{20}\text{O}_3$			<i>Radula uvifera</i>	(72)	
1517	Radulanin A-5-one	$\text{C}_{19}\text{H}_{18}\text{O}_3$			<i>Radula appressa</i>	(294)	
1518	β -Hydroxyradulanin A-5-one	$\text{C}_{19}\text{H}_{18}\text{O}_3$			<i>Marsupidium epiphyllum</i>	(635)	
1519	6-Hydroxy-4-(2-phenylethyl)benzofuran	$\text{C}_{16}\text{H}_{14}\text{O}_2$			<i>Marsupidium epiphyllum</i>	(635)	
					<i>Radula appressa</i>	(294)	
					<i>Radula buccinifera</i>	(72)	
					<i>Radula buccinifera</i>	(623)	
					<i>Radula oyamensis</i>	(623)	
					<i>Radula laxiramea</i>	(178)	
1520	(2 <i>R</i>)-Isopropenyl-6-hydroxy-4-(2-phenylethyl)dihydrobenzofuran	$\text{C}_{19}\text{H}_{20}\text{O}_2$			<i>Radula buccinifera</i>	(72)	
					<i>Radula uvifera</i>	(72)	
1521	3,5-Dihydroxy-4-(3-methyl-2-butenyl) bibenzyl	$\text{C}_{19}\text{H}_{22}\text{O}_2$			<i>Radula buccinifera</i>	(623)	
					<i>Radula laxiramea</i>	(72)	
					<i>Radula laxiramea</i>	(178)	
1522	3,5-Dihydroxy-4-(3-hydroxy-3-methylbutyl)bibenzyl	$\text{C}_{19}\text{H}_{24}\text{O}_3$			<i>Lepidozia vitrea</i>	(871)	
1523	2-Carboxy-3,5-dihydroxy-4-(3-methyl-2-butenyl)bibenzyl	$\text{C}_{20}\text{H}_{22}\text{O}_4$			<i>Radula laxiramea</i>	(178)	
1524	Amorfrutin [2-Carboxy-3-hydroxy-5-methoxy-4-(3-methyl-2-butenyl)bibenzyl]	$\text{C}_{21}\text{H}_{24}\text{O}_4$			<i>Radula laxiramea</i>	(178)	
1525	3,5-Dihydroxy-2-(3-methyl-2-butenyl) bibenzyl	$\text{C}_{19}\text{H}_{22}\text{O}_2$			<i>Lepidozia vitrea</i>	(871)	
					<i>Plagiochila permista</i>	(33)	
					var. <i>integerrima</i>	(33)	
					Unidentified	(33)	
					<i>Plagiochila</i> sp.	(72)	
					<i>Radula buccinifera</i>	(72)	
					<i>Radula brunea</i>	(623)	

			<i>Radula campanigera</i> (623)
			<i>Radula chinensis</i> (623)
			<i>Radula javanica</i> (623)
			<i>Radula kojana</i> (623)
			<i>Radula laxiramea</i> (178)
			<i>Radula marginata</i> (895)
			<i>Radula okamurana</i> (623)
			<i>Radula perrottetii</i> (492)
			<i>Radula sainsburiana</i> (635)
			<i>Radula uvifera</i> (72)
			(623)
			<i>Radula voluta</i> (447)
			Unidentified <i>Radula</i> sp. (612)
			<i>Radula buccinifera</i> (72)
			<i>Radula brunnea</i> (623)
			<i>Radula chinensis</i> (623)
			<i>Radula kojana</i> (623)
			<i>Radula obtusiloba</i> (623)
			<i>Platychila ovalifolia</i> (701)
			<i>Platychila satoi</i> (617)
			(84)
			<i>Radula brunnea</i> (84)
			<i>Radula brunnea</i> (84)
			<i>Radula perrottetii</i> (492)
			<i>Lepidozia vitrea</i> (871)
			<i>Radula appressa</i> (294)
			<i>Radula buccinifera</i> (72)
			(623)
			<i>Radula brunnea</i> (623)
			<i>Radula chinensis</i> (623)
1526	3-Hydroxy-5-methoxy-2-(3-methyl-2-butenyl)biphenyl	C ₂₀ H ₂₄ O ₂	
1527	3,5,4'-Trihydroxy-2-(3-methyl-2-butenyl) biphenyl	C ₁₉ H ₂₂ O ₃	
1528	α -Hydroxy-3,5-dihydroxy-2-(3-methyl-2-butenyl)biphenyl	C ₁₉ H ₂₂ O ₃	
1529	3,5-Dihydroxy-6-carbomethoxy-2-(3-methyl-2-butenyl)biphenyl	C ₂₁ H ₂₄ O ₄	
1530	2-Geranyl-3,5-dihydroxybiphenyl	C ₂₄ H ₃₀ O ₂	

(continued)

Table 4.5 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
					<i>Radula constricta</i>	(623)	
					<i>Radula grandis</i>	(72)	
						(623)	
					<i>Radula javanica</i>	(623)	
					<i>Radula kojana</i>	(623)	
					<i>Radula laxiramea</i>	(178)	
					<i>Radula lindenbergiana</i>	(623)	
					<i>Radula marginata</i>	(895)	
					<i>Radula obtusiloba</i>	(623)	
					<i>Radula okamuraana</i>	(623)	
					<i>Radula tokiensis</i>	(623)	
					<i>Radula uvifera</i>	(72)	
						(623)	
					<i>Radula voluta</i>	(447)	
					Unidentified <i>Radula</i> sp.	(612)	
					<i>Radula grandis</i>	(72)	
1531	2-(3,7-Dimethyl-2,7-octadienyl)-3,5-dihydroxybibenzyl	$\text{C}_{24}\text{H}_{30}\text{O}_2$				(72)	
1532	3,5-Dihydroxy-4-geranylbenzyl	$\text{C}_{24}\text{H}_{30}\text{O}_2$				(623)	
1533	3,5,4'-Trihydroxy-4-farnesylbenzyl	$\text{C}_{29}\text{H}_{38}\text{O}_3$			Unidentified <i>Radula</i> sp.	(84)	
						(612)	
1534	(2S)-2-Methyl-2-(4-methyl-3-pentenyl)-7-hydroxy-5-(2-phenylethyl)chromene (= o-Cannabichromene)	$\text{C}_{24}\text{H}_{28}\text{O}_2$			<i>Radula appressa</i>	(294)	
					<i>Radula buccinifera</i>	(72)	
					<i>Radula campanigera</i>	(623)	
					<i>Radula javanica</i>	(623)	
					<i>Radula kojana</i>	(623)	
					<i>Radula lindenbergiana</i>	(623)	
					<i>Radula obtusiloba</i>	(623)	
					<i>Radula tokiensis</i>	(623)	

1535	<i>o</i> -Cannabicyclol	$C_{24}H_{28}O_2$	<i>Radula appressa</i>	(294)
1536	2-Carboxy-5,4'-dihydroxy-3-methoxy-4,6-di-(3-methyl-2-butenyl)biphenyl	$C_{26}H_{32}O_5$	<i>Lethocolea glossophylla</i>	(447)
1537	3,5,4'-trihydroxy-2,4-di-(3-methyl-2-butenyl)biphenyl	$C_{24}H_{30}O_3$	<i>Lethocolea glossophylla</i>	(447)
1538	5-Hydroxy-2,2-dimethyl-6-(3-methyl-2-butenyl)-7-[2-(4'-hydroxyphenyl)-ethyl]chromene	$C_{24}H_{28}O_3$	<i>Lethocolea glossophylla</i>	(447)
1539	5-Hydroxy-2,2-dimethyl-7-[2-(4'-hydroxyphenyl)ethyl]-8-(3-methyl-2-butenyl)chromene	$C_{24}H_{28}O_2$	<i>Radula laxiramea</i>	(178)
1540	5-Hydroxy-2-methyl-2-(4-methyl-3-pentenyl)-7-(2-phenylethyl)chromene	$C_{19}H_{22}O_3$	<i>Radula perrottetii</i>	(84)
1541	Perrottetin A	$C_{19}H_{22}O_3$	<i>Radula perrottetii</i>	(492)
1542	2,2-Dimethyl-7,8-dihydroxy-5-(2-phenylethyl)chromene	$C_{19}H_{22}O_3$	<i>Radula marginata</i>	(895)
1543	2,2-Dimethyl-3,7-dihydroxy-5-(2-phenylethyl)chromane	$C_{19}H_{22}O_3$	<i>Radula marginata</i>	(895)
1544	2-(2-Hydroxy-3-methylbutenyl)-3,5-dihydroxybiphenyl	$C_{25}H_{28}O_4$	<i>Plagiochila ovalifolia</i>	(701)
1545	Perrottetinenic acid	$C_{24}H_{28}O_2$	<i>Radula marginata</i>	(895)
1546	Perrottetinene	$C_{26}H_{30}O_5$	<i>Radula marginata</i>	(895)
1547	2,2-Dimethyl-6-carbomethoxy-7-hydroxy-8-(3-methyl-2-butenyl)-5-[2-(4'-hydroxyphenyl)ethyl]chromene		<i>Radula campanigera</i>	(623)
			<i>Radula chinensis</i>	(623)
			<i>Radula laxiramea</i>	(178)
			<i>Radula marginata</i>	(895)
			<i>Marsipidium epiphyllum</i>	(635)

(continued)

Table 4.5 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1548	2-Carbomethoxy-3,5-dihydroxy-4,6-di-(3-methyl-2-butenyl)biphenyl	$\text{C}_{26}\text{H}_{32}\text{O}_4$			<i>Marsupidium epiphytum</i>	(635)	
1549	2-Carbomethoxy-3,5,4'-trihydroxy-4,6-di-(3-methyl-2-butenyl)biphenyl	$\text{C}_{26}\text{H}_{32}\text{O}_5$			<i>Marsupidium epiphytum</i>	(635)	
1550	2,4,6-Trichloro-3-hydroxybiphenyl	$\text{C}_{14}\text{H}_{11}\text{OCl}_3$			<i>Riccardia marginata</i>	(94)	
1551	2,4-Dichloro-3-hydroxybiphenyl	$\text{C}_{14}\text{H}_{12}\text{OCl}_2$			<i>Riccardia marginata</i>	(94)	
1552	2-Chloro-3-hydroxybiphenyl	$\text{C}_{14}\text{H}_{13}\text{OCl}$			<i>Riccardia marginata</i>	(94)	
1553	2,6-Dichloro-3-hydroxy-4'-methoxybiphenyl	$\text{C}_{15}\text{H}_{14}\text{O}_2\text{Cl}_2$			<i>Riccardia polyclada</i>	(458)	
1554	2,6,3'-Trichloro-3-hydroxy-4'-methoxybiphenyl	$\text{C}_{15}\text{H}_{13}\text{O}_2\text{Cl}_3$			<i>Riccardia polyclada</i>	(458)	
1555	2,4,6,3'-Tetrachloro-3-hydroxy-4'-methoxybiphenyl	$\text{C}_{15}\text{H}_{12}\text{O}_2\text{Cl}_4$			<i>Riccardia polyclada</i>	(458)	
1556	2,4,6,3'-Tetrachloro-3,4'-dihydroxybiphenyl	$\text{C}_{14}\text{H}_{10}\text{O}_2\text{Cl}_4$			<i>Riccardia polyclada</i>	(458)	
1557	2-[3-(Hydroxymethyl)phenoxy]-3-[2-(4-hydroxyphenyl)ethyl]phenol	$\text{C}_{21}\text{H}_{20}\text{O}_4$			<i>Marchantia polymorpha</i>	(210)	
1558	2'-(11-Hydroxy-1-biphenyl-oxy)-1'-methoxy-6',10',11'-trihydroxy-7',8'-dihydrophenanthrene	$\text{C}_{29}\text{H}_{26}\text{O}_6$			<i>Frullania convoluta</i>	(226)	
1559	2'-(10,11-Dihydroxy-1-biphenyl-oxy)-1'-methoxy-6',10',11'-trihydroxy-7',8'-dihydrophenanthrene	$\text{C}_{29}\text{H}_{26}\text{O}_7$			<i>Frullania convoluta</i>	(226)	
1560	(+)-Cavicularin	$\text{C}_{28}\text{H}_{22}\text{O}_4$	244-246	+168.2	<i>Cavicularia densa</i>	(875)	X-ray
1561	Dimeric prebiphenyl 1	$\text{C}_{30}\text{H}_{36}\text{O}_4$			<i>Balantiopsis rosea</i>	(84)	
1562	Dimeric prebiphenyl 2	$\text{C}_{30}\text{H}_{36}\text{O}_4$			<i>Balantiopsis rosea</i>	(84)	

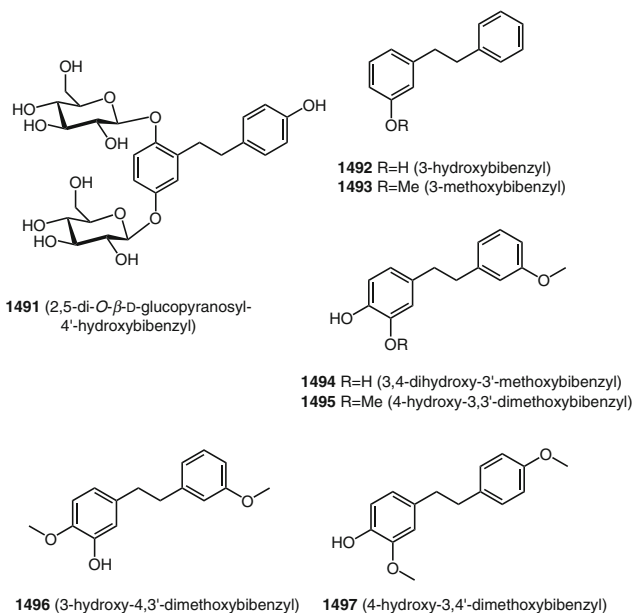
synthesis. Bis(allyl)-protected 3,4-dihydroxybenzaldehyde was treated with phosphonium salt prepared from 3-(bromomethyl)anisole to give the (*E*)- and (*Z*)-stilbene diastereomers; this was followed by deprotection of the allyl group to furnish the natural (*E*)-3,4-dihydro-3'-methoxy-stilbene and its (*Z*)-diastereomer (765).

The presence of bibenzyl glycosides in liverworts is very rare. *Qu* and associates isolated 2,5-di-*O*- β -D-glucopyranosyl-4'-hydroxybibenzyl (**1491**) from *Marchantia polymorpha* (667).

The CDCl₃ extract of the Scottish liverwort, *Plagiochila exigua*, showed the presence of a new bibenzyl, for which the structure was assigned as 3,4-dihydroxy-3'-methoxybibenzyl (**1494**), by the preparation of a diacetate and from NMR spectroscopic and GC/MS measurements (694).

An unidentified Costa Rican *Plagiochila* species, belonging to the section Permista, which is similar to *P. oresitropa* or *P. permista*, was found to produce 2-carboxy-4-hydroxy-3,4'-dimethoxybibenzyl (**1479**) (33), 3,4-dihydroxy-3'-methoxybibenzyl (**1494**), and 3,3'-dimethoxy-4-hydroxybibenzyl (**1495**), along with the known 3-methoxy-4'-hydroxybibenzyl (**1482**) (34).

Four simple bibenzyls, 3-hydroxy-4,3'-dimethoxybibenzyl (**1496**), 3-hydroxy-4,5-methylenedioxy-3'-methoxybibenzyl (**1498**), brittonin B (**1499**), and 3,4:3'4'-dimethylenedioxybibenzyl (**1500**), were obtained from a New Zealand *Frullania* species (78). 4-Hydroxy-3,4'-dimethoxybibenzyl (**1497**) was also identified from *Frullania muscicola* (484). 3,4,3'-Trimethoxybibenzyl (**1502**) was isolated from the Argentinean *Frullania brasiliensis*, and structure was deduced by 2D-NMR spectroscopic data interpretation (98).



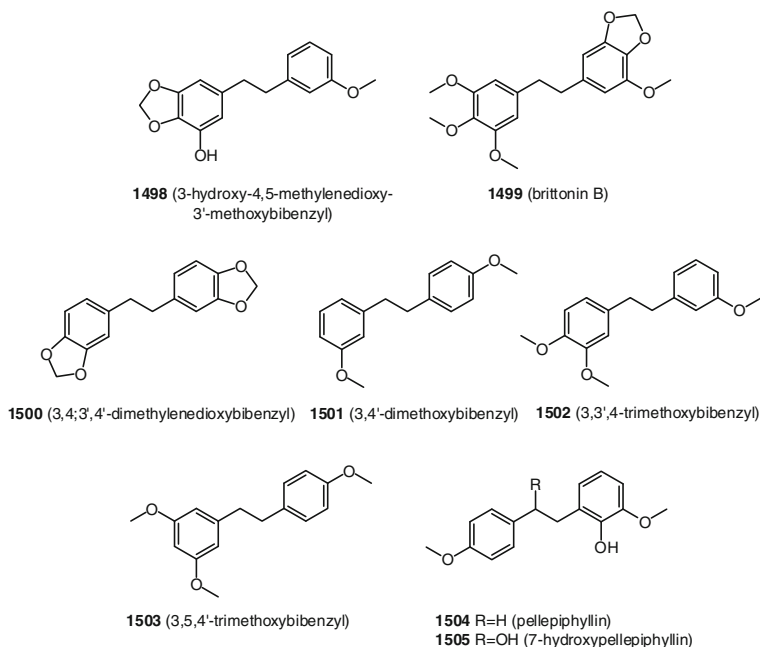
Bibenzyls found in the Marchantiophyta

German and Chinese collections of *Monoselenium tenerum* belonging to the Monoseleniaceae were found to be very simple as viewed from a chemical

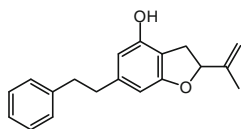
perspective. On TLC and GC, only two spots and two peaks appeared. The predominant components were the new bibenzyl 3,5,4'-trimethoxybibenzyl (**1503**) and the known phthalide, 3-(4'-methoxybenzyl)-5,7-dimethoxyphthalide (**1807**) (Sect. 4.5.3). The structure of the former compound was characterized from its 2D-NMR and mass spectrometric data (492).

Reinvestigation of the ether extract of the gametophytes of the European *Pellia epiphylla* resulted in the isolation of the two bibenzyls **1504** and **1505**. The structure of **1504** was proposed as pellepiphyllin by analysis of its NMR spectra. Compound **1505** was also isolated from the sporophytes of *P. epiphylla* (175). Conclusive evidence for the structure was proved by its total synthesis. The Wittig reaction of 2-benzyloxy-3-methoxybenzaldehyde and the (*p*-methoxybenzyl)-phosphonium salt gave 2-benzyloxy-3,4'-dimethoxystilbene, which was followed by hydrogenation to afford pellepiphyllin (**1504**). The structure of 7-hydroxypellepiphyllin (**1505**) was deduced by comparison of its spectroscopic data with those of compound **1504**. Compound **1505** showed levorotatory optical rotations at 365 and 436 nm (175, 182).

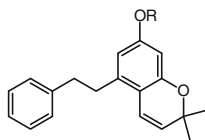
The previously known 2,2-dimethyl-7-hydroxy-5-(phenylethyl)chromene (**1507**) and its methyl ether, 2,2-dimethyl-7-methoxy-5-(2-phenylethyl)chromene (**1508**) were detected in nine *Radula* species (623), *Plagiochila* species (33), and *Tylimanthus saccatus* (72). Isomers **1509** and **1510** of **1507** and **1508** have also been frequently found in *Radula* species, as shown in Table 4.5 (223, 623).



Bibenzyls found in the Marchantiophyta

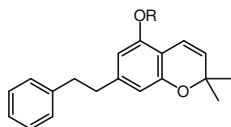


1506 (tylimanthin B)



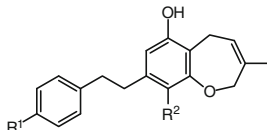
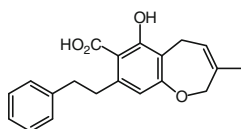
1507 R=H (2,2-dimethyl-7-hydroxy-5-(2-phenylethyl)chromene)

1508 R=Me (2,2-dimethyl-7-methoxy-5-(2-phenylethyl)chromene)

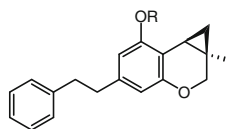


1509 R=H (2,2-dimethyl-5-hydroxy-7-(2-phenylethyl)chromene)

1510 R=Me (2,2-dimethyl-5-methoxy-7-(2-phenylethyl)chromene)

1511 R¹=R²=H (radulanin A)1512 R¹=OH, R²=H (radulanin C)1512a R¹=H, R²=CO₂H

1513 (radulanin H)



1514 R=H (radulanin I)

1515 R=Me (radulanin J)

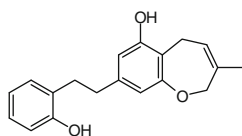
Bibenzyls found in the Marchantiophyta

Radulanin H (**1513**) has been isolated from *Radula complanata* (40). The same compound was identified also by Figueiredo and associates in *Radula lindenberiana* (223).

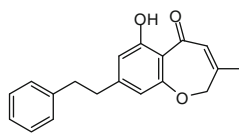
The total syntheses of radulanin E (**1512a**), isolated from the liverwort *R. valabilis* (39), and radulanin H (**1513**), from *P. perrottetii* (40), were achieved by Yoshida and colleagues using an intramolecular condensation, sequential regioselective C- and O-allylations of 2,4-dihydroxy-6-phenylethylbenzoic acid ethyl ester, and ring closing metathesis, as the key steps (970). Yamaguchi and coworkers also achieved the total synthesis of **1512a** and **1513** by intermolecular Mitsunobu cyclization for construction of the seven-membered ring (969).

The Australian *Radula buccinifera* elaborates five bibenzyls, 3-methoxybibenzyl (**1493**), 3,4'-dimethoxybibenzyl (**1501**), radulanin A (**1511**), radulanin C (**1512**), and 3,5-dihydroxy-4-(3-methyl-2-butenyl)bibenzyl (**1525**) (40). Further investigation of the ether extract of a New Zealand specimen of this liverwort resulted in the identification of the bibenzyls mentioned immediately above as well as 6-hydroxy-4-(2-phenylethyl)benzofuran (**1519**), (2*R*)-isopropenyl-6-hydroxy-4-(2-phenylethyl)dihydrobenzofuran (**1520**), and 3,5-dihydroxy-2-(3-methyl-2-butenyl)bibenzyl (**1525**), of which the latter has been found in *Radula sainsburiana* collected in New Zealand (635). The Japanese *Plagioclila ovalifolia* contained 3,5-dihydroxy-2-(3-methyl-2-butenyl)bibenzyl (**1525**),

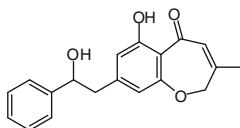
together with 3-hydroxy-5-methoxy-2-(3-methyl-2-butenyl)bibenzyl (**1526**), 2-geranyl-3,5-dihydroxybibenzyl (**1530**), and (2*S*)-2-methyl-2-(4-methyl-3-pentenyl)-7-hydroxy-5-(2-phenylethyl)chromene **1534** (701). Compounds **1525** and **1530** have been recognized as highly significant chemical markers of the genus *Radula* (40, 45).



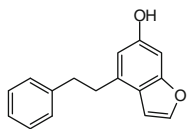
1516 (radulanin L)



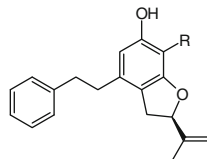
1517 (radulanin A-5-one)



1518 (β-hydroxyradulanin A-5-one)

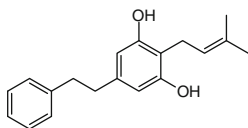


1519 (6-hydroxy-4-(2-phenylethyl) benzofuran)

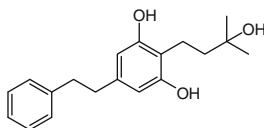


1520 R=H ((2*R*)-isopropenyl-6-hydroxy-4-(2-phenylethyl)dihydrobenzofuran)
1520a R=OH (perrottetin D)

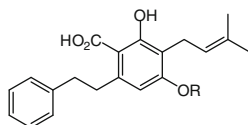
Bibenzyls found in the Marchantiophyta



1521 (3,5-dihydroxy-4-(3-methyl-2-butenyl)biphenyl)

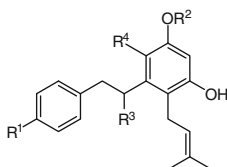


1522 (3,5-dihydroxy-4-(3-hydroxy-3-methylbutyl)biphenyl)



1523 R=H (2-carboxy-3,5-dihydroxy-4-(3-methyl-2-butenyl)biphenyl)

1524 R=Me (amorfrutin)



1525 R¹=R²=R³=R⁴=H (3,5-dihydroxy-2-(3-methyl-2-butenyl)biphenyl)

1526 R¹=R³=R⁴=H, R²=Me (3-hydroxy-5-methoxy-2-(3-methyl-2-butenyl)biphenyl)

1527 R¹=OH, R²=R³=R⁴=H (3,5,4'-trihydroxy-2-(3-methyl-2-butenyl)biphenyl)

1528 R¹=R²=R⁴=H, R³=OH (α -hydroxy-3,5-dihydroxy-2-(3-methyl-2-butenyl)biphenyl)

1529 R¹=R²=R³=H, R⁴=CO₂Me (3,5-dihydroxy-6-carbomethoxy-2-(3-methyl-2-butenyl)biphenyl)

Biphenyls found in the Marchantiophyta

Fractionation of the ether extract of the New Zealand *Marsupidium epiphytum* resulted in the isolation of two new biphenyls with an dihydrooxepin skeleton, with their structures assigned as radulanin A-5-one (**1517**) and β -hydroxyradulanin-5-one (**1518**) by 2D-NMR spectroscopic data interpretation. The configuration of a secondary hydroxy group at the β -position of the phenylethyl moiety remained to be clarified (**635**).

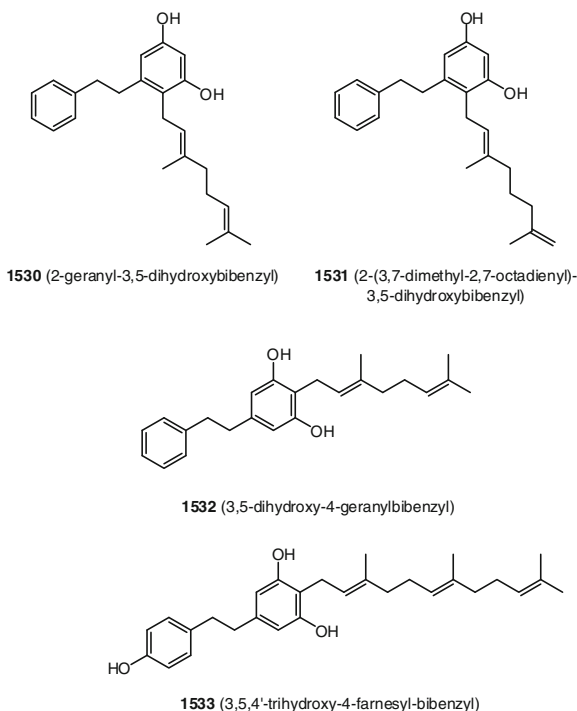
The Japanese *Plagiochila satoi* produced not only the 2,3-secoaromadendrane sesquiterpenoid, plagiochiline C (**185**), but also the new prenyl biphenyl **1527**, with its structure established as 3,5,4'-trihydroxy-2-(3-methyl-2-butenyl)biphenyl, by comparison of its ¹H NMR spectrum with that of 2-(3-methyl-2-butenyl)-3,5-dihydroxybiphenyl (**1525**). This was the first report of the isolation of a prenyl biphenyl from the Plagiochilaceae (**617**).

The ether extract of *Lepidozia vitrea* was purified by passage over Sephadex LH-20 to afford the known 3,5-dihydroxy-2-(3-methyl-2-butenyl)biphenyl (**1525**) and 2-geranyl-3,4-dihydroxybiphenyl (**1530**). This constituted the first record of the isolation of prenyl biphenyls from the family Lepidoziaceae (**871**).

Radula grandis, collected in New Zealand, produced radulanins A (**1511**), I (**1514**), and J (**1515**), 2-geranyl-3,5-dihydroxybiphenyl (**1530**), 2-(3,7-dimethyl-2,7-

octadienyl)-3,5-dihydroxybibenzyl (**1531**), and 3,5-dihydroxy-4-geranylbibenzyl (**1532**). *Radula uvifera*, also from New Zealand, is closely related chemically to *R. grandis* since it produces the same bibenzyls (**1514**, **1515**, **1530**) as found in the latter species (72).

A New Zealand unidentified *Radula* species was found to elaborate a new bibenzyl, for which the structure was proposed as 4-farnesyl-3,5,4'-trihydroxybibenzyl (**1533**) by NMR spectroscopic data analysis (612), together with the two known bibenzyls, **1525** and **1530** (40), which were also isolated from the Ecuadorian *R. voluta* (447). A similar compound to **1533**, namely, 3,5-dihydroxy-4-geranylbibenzyl (**1532**), was found in the same genus (40).



Prenylbibenzyls found in the Marchantiophyta

Harinantenaina and colleagues (294) reported that the Madagascan species *Radula appressa* produces radulanin A (**1511**), radulanin L (**1516**), 6-hydroxy-4-(2-phenylethyl)benzofuran (**1519**), 2-geranyl-3,5-dihydroxybibenzyl (**1530**), (2*S*)-2-methyl-2-(4-methyl-3-pentenyl)-7-hydroxy-5-(2-phenylethyl)chromene (= *o*-cannabichromene) (**1534**) (40), and *o*-cannabicyclol (**1535**) (172, 173).

The dichloromethane extract of the Costa Rican *Radula laxiramea* was fractionated by column chromatography to give the two new bibenzyl derivatives **1522** and **1540**, together with the prenyl bibenzyls **1521**, **1523**, **1525**, and **1530**, the chromone **1509**, the benzofuran **1519**, the salicylic acid derivative, amorfrutin

A (**1524**), the bibenzyl cannabinoid, perrottetinene (**1546**) (*178*), and the common bis-bibenzyl, perrottetin E (**1636**) (*40*). The structures of the new products **1522** and **1540** were determined as 3,5-dihydroxy-4-(3-hydroxy-3-methylbutyl)bibenzyl and 5-hydroxy-2-methyl-2-(4-methyl-3-pentenyl)-7-(2-phenylethyl)chromene by analysis of their ^1H - and ^{13}C NMR spectra and comparison with those of compounds **1521** and **1524**. The salicylic acid derivative, 2-carboxy-3,5-dihydroxy-4-(3-methyl-2-butenyl)bibenzyl (**1523**), was also isolated. Compound **1540** was obtained for the first time as a natural product although it has been synthesized during a study of bibenzyl cannabinoids from *Cannabis sativa* (*255*). The isomer of **1540**, (2*S*)-2-methyl-2-(4-methyl-3-pentenyl)-7-hydroxy-5-(2-phenylethyl)chromene, was isolated from *Radula kojana* (*40*).

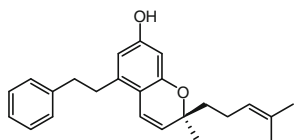
An ether extract of *Radula perrottetii*, collected in a different locality than previously, was reinvestigated chemically to give 3,5-dihydroxy-6-carbomethoxy-2-(3-methyl-2-butenyl)bibenzyl (**1529**), perrottetin A (**1541**), 2,2-dimethyl-7,8-dihydroxy-5-(2-phenylethyl)chromene (**1542**), and the bibenzyl cannabinoid perrottetinene (**1546**), all of which were isolated previously from this same species (*492*). *Radula brunnea* was analyzed phytochemically, leading to the isolation of the new α -hydroxy-3,5-dihydroxy-2-(3-methyl-2-butenyl)bibenzyl (**1528**), for which the structure was based on a comparison of its spectroscopic data with those of **1525** (*84*).

The ether extract of the New Zealand liverwort *Radula marginata* was fractionated to give the three new bibenzyl derivatives **1543–1545**, together with the known bibenzyl cannabinoid perrottetinene (**1546**) as well as 2-(3-methyl-2-butenyl)-3,5-dihydroxybibenzyl (**1525**), 2-geranyl-3,5-dihydroxybibenzyl (**1530**), and δ -tocopherol (**1877**). The structures of **1543** and **1544** were established as 2,2-dimethyl-3,7-dihydroxy-5-(2-phenylethyl)chromane and 2-(2-hydroxy-3-methylbutenyl)-3,5-dihydroxybibenzyl, by analysis of 2D-NMR (HMBC, HMQC, and NOESY) spectroscopic data. The structure of compound **1545**, perrottetinenic acid, was determined by comparison with the NMR spectra of perrottetinene (**1546**), although the absolute configuration remained to be clarified (*84, 895*). Perrottetinenic acid (**1545**) was isolated also from the Japanese *Plagiochila ovalifolia* (*701*).

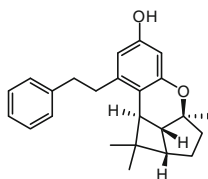
Radula species are especially rich sources of bibenzyls and prenyl bibenzyls. Two of the most interesting bibenzyls are the bibenzyl tetrahydrocannabinoids **1545** and **1546**. *Crombie* and associates predicted the occurrence of such bibenzyls and synthesized bibenzyl tetrahydrocannabinoids possessing *trans*- geometry at the cyclohexane ring (*173*). Their prediction was confirmed by the isolation of the bibenzyl cannabinoid derivative, (–)-perrottetinene (**1546**), containing a *cis*- moiety, from the liverwort *Radula perrottetii* (*866*). *Song et al.* accomplished the total synthesis of (–)-perrottetinene (**1546**) [$\alpha_{\text{D}} -118.2^\circ \text{ cm}^2 \text{ g}^{-1} 10^{-1}$ [lit. $-121.3^\circ \text{ cm}^2 \text{ g}^{-1} 10^{-1}$ (*866*)] in nine steps and 15% overall yield from 3,5-dihydroxybibenzyl (*763*).

The dichloromethane extract of the Ecuadorian *Lethocolea glossophylla*, belonging to the Acrobolbaceae, was found to contain five new prenyl bibenzyls, 2-carboxy-5,4'-dihydroxy-3-methoxy-4,6-di-(3-methyl-2-butenyl)bibenzyl (**1536**), 3,5,4'-trihydroxy-2,4-di-(3-methyl-2-butenyl)bibenzyl (**1537**), 5-hydroxy-2,2-dimethyl-6-(3-methyl-2-butenyl)-7-[2-(4'-hydroxyphenyl)-ethyl]-chromene (**1538**), and 5-hydroxy-2,2-dimethyl-7-[2-(4'-hydroxyphenyl)-ethyl]-8-(3-methyl-2-butenyl)

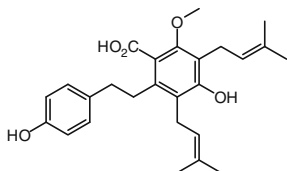
chromene (**1539**), and the new bibenzyl, glossophyllin (**1563**). Their structures were elucidated by a combination of MS and 2D-NMR data analysis. The 3D-structure of glossophyllin (**1563**) was also deduced by calculation using molecular dynamics simulation. This was the first report of the isolation of a bisprenylated bis-bibenzyl with a chromene and a chromane moiety as a natural product ([447](#)). It is noteworthy that all of the isolated compounds from *L. glossophylla* have two prenyl groups. However, on the other hand, monoprenyl bibenzyls have been found in many *Radula* species.



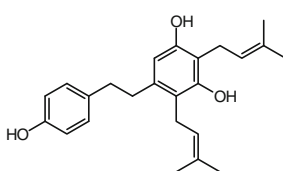
1534 ((2*S*)-2-methyl-2-(4-methyl-3-pentenyl)-7-hydroxy-5-(2-phenylethyl)chromene)



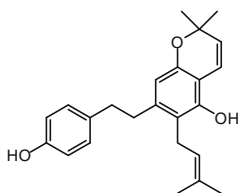
1535 (*o*-cannabicyclol)



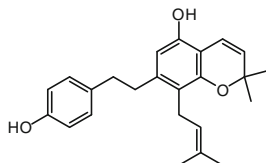
1536 (2-carboxy-5,4'-dihydroxy-3-methoxy-4,6-di-(3-methyl-2-butenyl)bibenzyl)



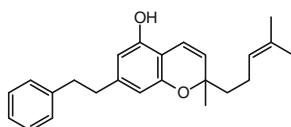
1537 (3,5,4'-trihydroxy-2,4-di-(3-methyl-2-butenyl)bibenzyl)



1538 (5-hydroxy-2,2-dimethyl-6-(3-methyl-2-butenyl)-7-[2-(4'-hydroxyphenyl)ethyl]chromene)

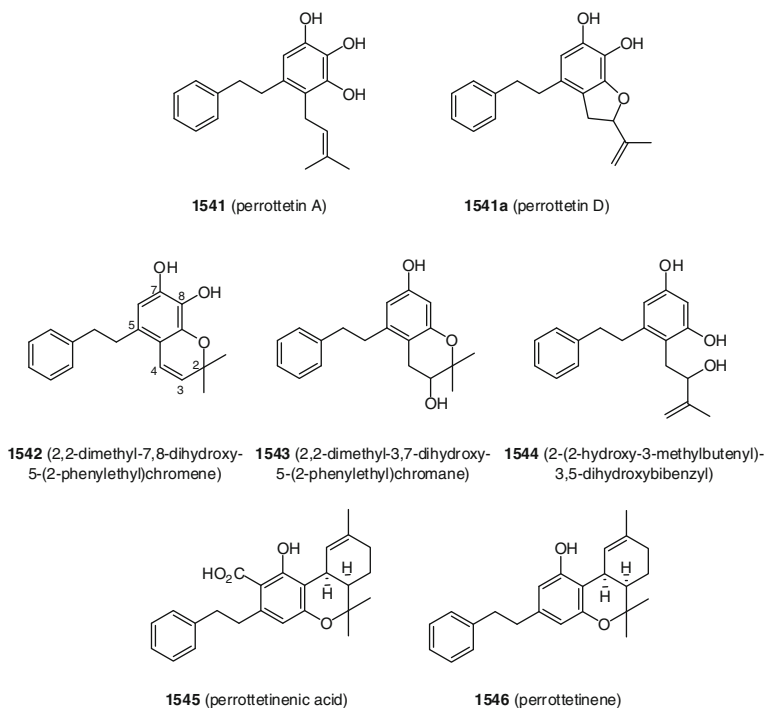


1539 (5-hydroxy-2,2-dimethyl-7-[2-(4'-hydroxyphenyl)ethyl]-8-(3-methyl-2-butenyl)chromene)



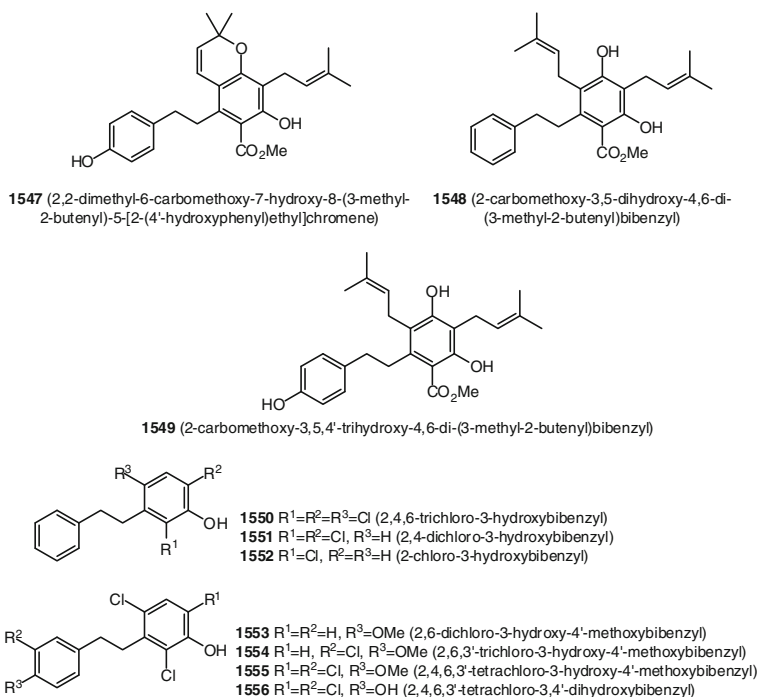
1540 (5-hydroxy-2-methyl-2-(4-methyl-3-pentenyl)-7-(2-phenylethyl)chromene)

Prenylbibenzyls found in the Marchantiophyta



Prenylbibenzyls and bibenzylcannabinoids found in the Marchantiophyta

The New Zealand *Marsipidium epiphytum* was reported to produce the three new bibenzyls **1547**–**1549**. The presence of *p*-hydroxybenzyl, a hydrogen-bonded hydroxy group, and a carbomethoxy functionality in compound **1547** was deduced by an ion peak at m/z 107 in the MS, an absorption band at $1,652\text{ cm}^{-1}$ in the IR spectrum, and resonances at δ_{H} 11.66 and 3.95 ppm in the ^1H NMR spectrum. The complete structure of **1547** was determined to be 2,2-dimethyl-6-carbomethoxy-7-hydroxy-8-(3-methyl-2-butenyl)-5-[2-(4'-hydroxyphenyl)ethyl]chromene by 2D-NMR data interpretation, including the COSY and HMBC spectra. The elucidation of the structure of **1548** was also carried out by a combination of 1D-NMR, MS, and IR data analysis. Compound **1548** was found to possess two phenolic hydroxy groups, a carbomethoxy, and two 2,2-dimethylallyl units as well as a phenyl ethyl moiety. The location of each functional group was established by 2D-NMR spectroscopic methods, and the whole structure proposed as 2-carbomethoxy-3,5-dihydroxy-4,6-di-(3-methyl-2-butenyl)bibenzyl. Compound **1549** was similar spectroscopically to **1548** except for resonances due to the presence of one additional hydroxy group. The occurrence of a mass spectrometric fragment ion at m/z 107 indicated that **1549** is 2-carbomethoxy-3,5,4'-trihydroxy-4,6-di-(3-methyl-2-butenyl)bibenzyl (**635**).



Prenyl- and chlorinated bibenzyls found in the Marchantiophyta

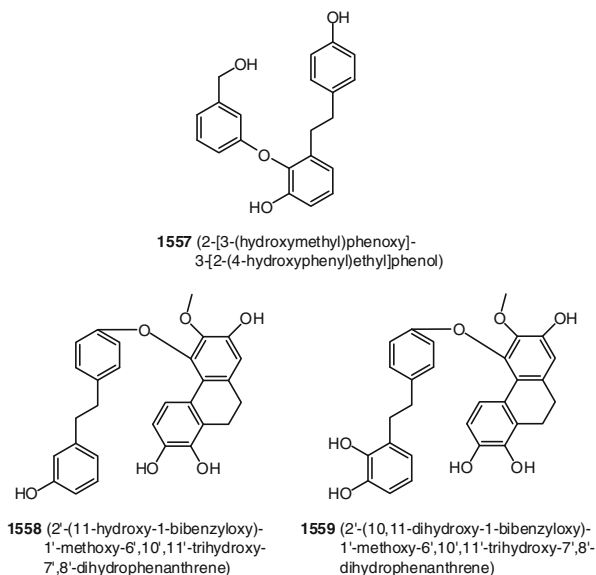
The chloroform extract of *Riccardia maginata*, a liverwort endemic to New Zealand, was chromatographed on octadecyl-functionalized silica gel to give the three new chlorinated bibenzyls, 2,4,6-trichloro-3-hydroxybibenzyl (**1550**), 2,4-dichloro-3-hydroxybibenzyl (**1551**), and 2-chloro-3-hydroxybibenzyl (**1552**). This represents the first record of simple chlorinated bibenzyls from any natural source (94). The structures of these three compounds were elucidated by analysis of a combination of their mass spectrometric and 2D-NMR data. Compounds **1550–1552** might accumulate in their species of origin through chlorination of 3-hydroxybibenzyl (**1492**) by a haloperoxidase, which was found in the liverwort *Bazzania trilobata* (768). 3-Hydroxybibenzyl (**1492**) has been found in *Radula frondescens* (40). However, this precursor for the chlorinated compound has not been detected in *R. marginata*. Baek and colleagues predicted that compounds **1550–1552** protect the liverwort against pathogenic bacteria and fungi since they showed antimicrobial and antifungal activity. It is curious that the same species collected in other locations did not contain these halogenated compounds (94). Four similar chlorinated bibenzyls, 2,6-dichloro-3-hydroxy-4'-methoxybibenzyl (**1553**), 2,6,3'-trichloro-3-hydroxy-4'-methoxybibenzyl (**1554**), 2,4,6,3'-tetrachloro-3-hydroxy-4'-methoxybibenzyl (**1555**), and 2,4,6,3'-tetrachloro-3,4'-dihydroxybibenzyl (**1556**) were isolated from the dichloromethane extract of the Chilean *Riccardia polyclada*. Their structures were determined by a combination of high-resolution chemical ionization mass spectrometry (HRCIMS) and heteronuclear correlation (HETCOR) NMR spectroscopy (458). These perchlorinated compounds



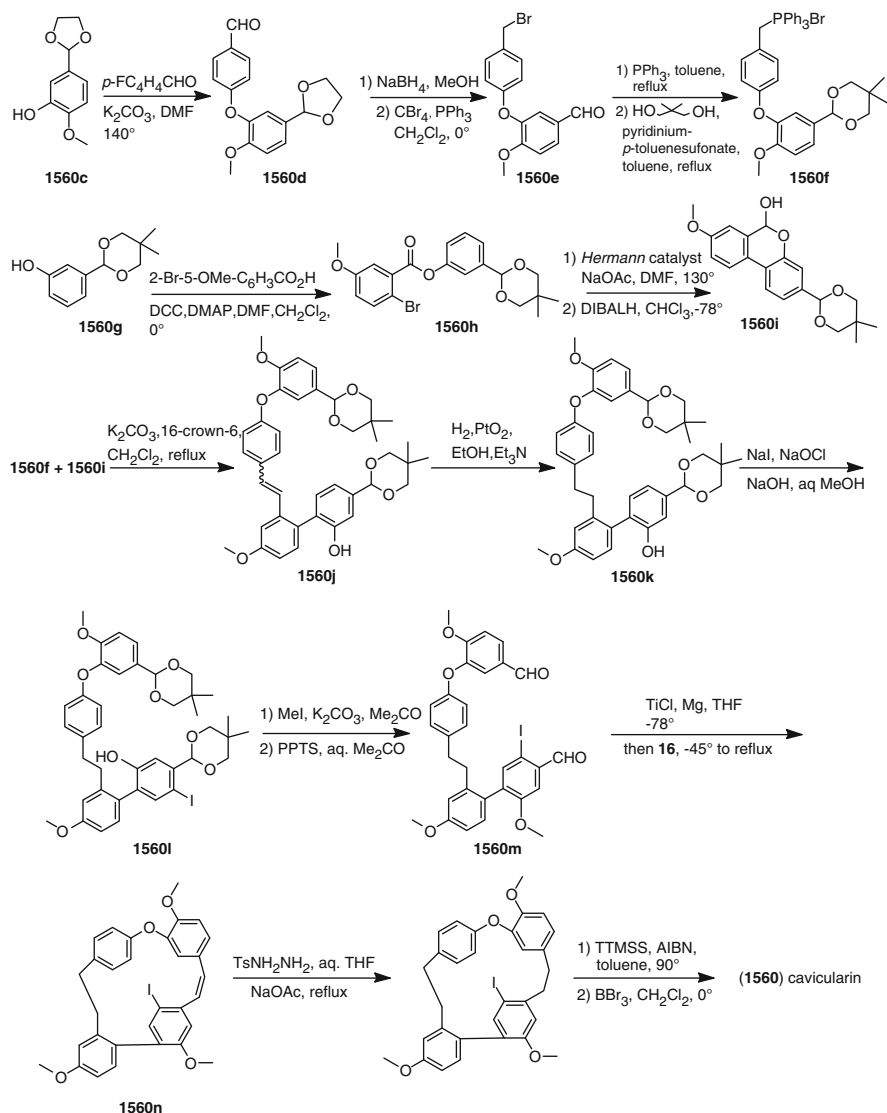
Fig. 4.19 *Cavicularia densa*. (Permission for the use of this figure has been obtained from Mr. Masana Izawa, Saitama, Japan)

also showed antifungal activity against *Cladosporium herbarum*, antifeedant activity against *Spodoptera littoralis*, and brine shrimp lethality activity (see Chap. 6). Naturally occurring organohalogenated compounds have been isolated from a great number of marine organisms (270).

From the ether extract of Chinese *Marchantia polymorpha*, the new phenoxybibenzyl **1557** was isolated together with bis-bibenzyl perrottetin E (**1638**) (see Sect. 4.5.2). For this compound, the structure of 2-[3-(hydroxymethyl)phenoxy]-3-[2-(4-hydroxyphenyl)ethyl]phenol (**1557**) was proposed from 2D-NMR experiments, inclusive of analysis of the HMBC spectrum (210).



Phenoxy- and dihydrophenanthrenyloxybibenyls found in the Marchantiophyta



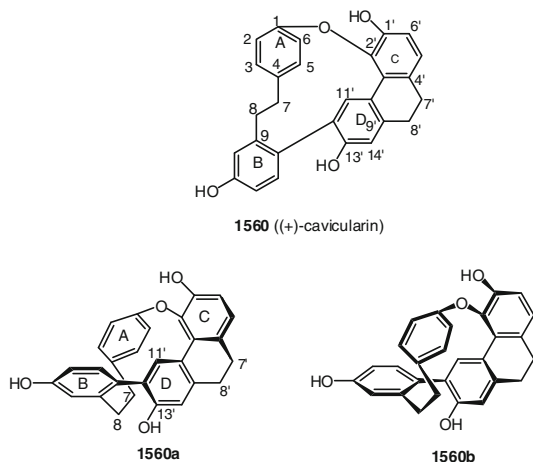
DMF = *N,N*-dimethylformamide, DCC = dicyclohexylcarbodiimide, DMAP = 4-dimethylaminopyridine, DIBALH = diisobutylaluminum hydride, TS = *p*-toluenesulfonyl, TTMSS = tris(trimethylsilyl)silane, AIBN = azobis(isobutyronitrile)

Scheme 4.50 Total synthesis of cavicularin (1560)

A methanol-soluble extract of the Ecuadorian *Frullania convoluta* was fractionated to afford 2'-(11-hydroxy-1-bibenzyloxy)-1'-methoxy-6',10',11'-trihydroxy-7',8'-dihydrophenanthrene (**1558**) and 2'-(10,11-dihydroxy-1-bibenzyloxy)-1'-methoxy-6',10',11'-trihydroxy-7',8'-dihydrophenanthrene (**1559**), along with

lunularin (**1477**) and lunularic acid (**1478**). Their structures were established by a combination of HMBC and NOESY spectroscopic data interpretation and the overall spectroscopic similarity to lunularin (**1477**) (226).

The rare Japanese liverwort *Cavicularia densa* (Fig. 4.19), which belongs to the same family, Blasiaceae, as *Blasia pusilla*, produced the novel optically active cyclic compound, (+)-cavicularin (**1560**) which is among the most unusual natural products found in the last decade. This macrocyclic compound has a bibenzyl and dihydrophenanthrene unit conjugated by a biaryl bond and an ether linkage. The structure was established by a combination of 2D-NMR (^1H - ^1H , NOESY, HMQC, HMBC) and X-ray crystallographic analysis. The absolute structure of **1560** could be restricted to **1560a** or **1560b** from the X-ray crystallographic studies. The phenanthrene-bibenzyl skeleton possesses a highly strained structure and the benzene ring A was twisted out of the plane by 15° in the solid state. Although the structure of **1560** has no chiral center, its specific optical rotation showed $[\alpha]_{\text{D}} +168.2 \text{ cm}^2 \text{ g}^{-1}$ and Cotton effects due to the $\pi - \pi^*$ transition of the asymmetric aryls ($\lambda(\Delta\epsilon) = 312(+4.6)$, $280(+2.6)$, $255(-2.6)$, $208(+24.6) \text{ nm}(\text{mol}^{-1} \text{ dm}^3 \text{ cm}^{-1})$). This phenomenon suggested that **1560** possesses both planar and axial chirality (875). Such a rare cavicularin-type bibenzyl has not been found in any other liverwort so far. Compound **1560** might be formed by intramolecular phenolic oxidative coupling between C-3' and C-10' from riccardin C (**1566**) isolated from *Blasia pusilla*, which produces the riccardin C dimers, pusilatins A-D (**1650–1653**) (see Sect. 4.5.2) (40). Harrowven and associates succeeded in the first total synthesis of cavicularin using isovanillin as the starting material, as shown in Scheme 4.50 (301).



The dihydrophenanthrenyloxybibenzyl **1560** found in the Marchantiophyta

The New Zealand *Balantiopsis rosea* elaborates unique sulfur-containing benzyl and β -phenylethyl acrylates (40). This species has also been reported to produce

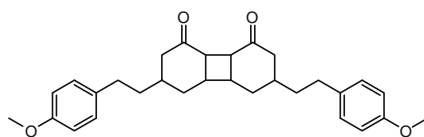


Fig. 4.20 *Riccardia* species. (Permission for the use of this figure has been obtained from Prof. Dr. Rob Gradstein, Paris, France)

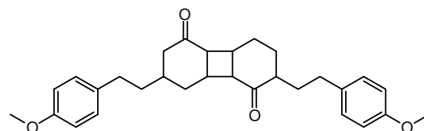


Fig. 4.21 *Marchantia polymorpha* (female thallus)

three prebibenzyls, as mentioned above, together with the two unique dimeric prebibenzyls, **1561** and **1562**, for which their structures were settled from 2D-NMR spectroscopic data. Those dimers might be formed from longispinone A (**1474**), which co-occurs in the same species (84).



1561 (dimeric prebibenzyl 1)

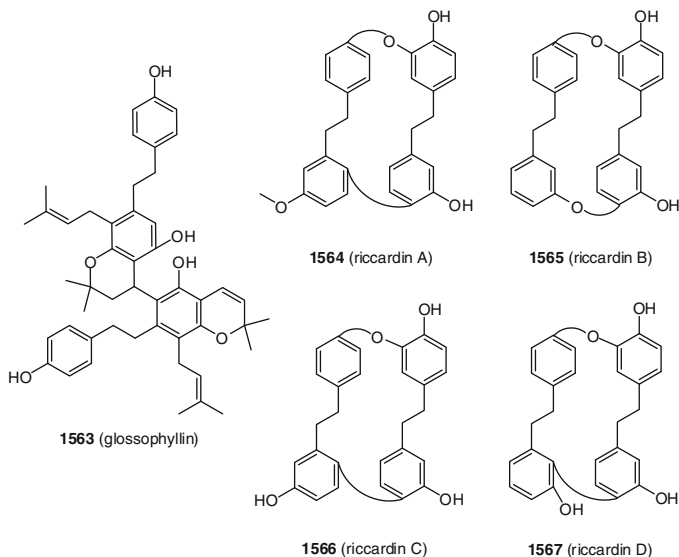


1562 (dimeric prebibenzyl 2)

Dimeric bibenzyls found in the Marchantiophyta

4.5.2 Bis-bibenzyls

Since initial reports of two macrocyclic bis-bibenzyls, riccardin A (**1564**) and marchantin A (**1577**), isolated from the Japanese *Riccardia multifida* (Fig. 4.20) and *Marchantia polymorpha* (Fig. 4.21) (39), more than 50 new bis-bibenzyls have been isolated from these same liverworts and other species belonging to the Jungermanniales, Marchantiales, Metzgeriales, and Monocleales, and their structures elucidated (40). However, these structurally rare compounds have not yet been found in the Bryophyta and Anthocerotophyta. Since 1995, the new bis-bibenzyls **1570**, **1572–1576**, **1597–1602**, **1608–1637**, **1641–1644**, **1646–1651**, and **1656–1659** have been isolated from the Marchantiophyta, as shown in Table 4.6 (40).



Bis-bibenzyls found in the Marchantiophyta

The occurrence, conformation, biosynthesis, biological activity, and synthesis of bis-bibenzylys have been reviewed by Asakawa's group (40, 76, 85) and Keseru and Nogradi (402, 403). Bringmann and Menche reviewed biaryls, including bis-bibenzylys, plagiochin, the chlorinated bis-bibenzylys, and compounds in the bazzanin series (133).

Such macrocyclic bis-bibenzylys are very rare plant metabolites possessing structures that occur exclusively in the Marchantiophyta. It is noteworthy that an acetone extract of the higher plant, *Primula macrocalyx* (Primulaceae), which has been used in folk medicine to treat paralysis, scurvy, tuberculosis, and fever, was fractionated by column chromatography using a reversed-phase resin to give a bis-bibenzyl identified as riccardin C (1566) (439). This is the first record of the isolation of this macrocyclic bis-bibenzyl from a higher plant. On the other hand, the acyclic bis-bibenzyl, perrottetin H (2206), has been isolated from the Japanese fern, *Hymenophyllum barbatum* (633). Such characteristic bis-bibenzylys are not only very significant chemical markers of several Marchantiophyta families but also important for considering the phylogeny of the bryophytes and the evolutionary processes of the lower terrestrial spore-forming plants (see Chap. 9.).

The naturally occurring bis-bibenzylys are categorized into three structural types, which are made up of macrocyclic rings linked *via* two biphenyl ether C-O bonds, one biphenyl ether C-O, one biaryl C-C bond, and two biphenyl bonds.

A previous study on the chemical constituents of *Riccardia multifida* subsp. *decrescens* showed that this tiny liverwort produces two macrocyclic bis-bibenzylys, riccardins A (1564) and B (1565) (40, 583). From the ether extract of *Riccardia nagasakiensis*, riccardin A (1564) and marchantin C (1579) were isolated (141). Riccardin C (1566) was isolated initially from the Japanese *Reboulia hemisphaerica* (53). A specimen of *Mastigophora diclados* collected in Madagascar also contained riccardin C (1566) (287). *Reboulia hemisphaerica* produces not only riccardin-type bibenzylys but also the marchantin-type compound, marchantin C (1579) (242).

A Chinese collection of *Dumortiera hirsuta* (487) and the Taiwanese *Jungermannia infusca* (952) elaborated riccardin C (1566) and marchantin C (1579). The former species also gave riccardin D (1567) (487). The methanol extract of *Marchantia tosona* was reinvestigated chemically to afford riccardin C (1566), riccardin F (1568), and marchantin A (1577), of which riccardin C was found for the first time in this species (347).

Table 4.6 Bis-bibenzylys found in the Marchantiophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2 \text{g}^{-1} 10^{-1}$	Plant source	References	Comments
1563	Glossophyllin	$\text{C}_{48}\text{H}_{56}\text{O}_6$		+1.2	<i>Lethocolea glossophylla</i>	(447)	
1564	Riccardin A	$\text{C}_{29}\text{H}_{26}\text{O}_4$			<i>Riccardia multifida</i> <i>Riccardia multifida</i> subsp. <i>decrescens</i>	(583) (972)	
1565	Riccardin B	$\text{C}_{28}\text{H}_{24}\text{O}_4$			<i>Riccardia nagasakiensis</i> <i>Asterella angusta</i> <i>Preissia quadrata</i>	(141) (666) (74)	
1566	Riccardin C	$\text{C}_{28}\text{H}_{24}\text{O}_4$			<i>Riccardia multifida</i> <i>Blasia pusilla</i> <i>Dumortiera hirsuta</i>	(583) (971) (487)	
					<i>Jungermannia infusca</i> <i>Mastigophora dicladus</i> <i>Plagiochasma intermedium</i> <i>Plagiochasma</i> <i>pterospermum</i>	(883) (952) (287) (967) (314)	
1567	Riccardin D	$\text{C}_{28}\text{H}_{24}\text{O}_4$			<i>Plagiochasma rupestre</i> <i>Plagiochila</i> sp. <i>Asterella angusta</i> <i>Dumortiera hirsuta</i> <i>Marchantia polymorpha</i> <i>Plagiochasma japonica</i> <i>Plagiochila cristata</i> <i>Blasia pusilla</i> <i>Plagiochasma intermedium</i> <i>Marchantia chenopoda</i> <i>Marchantia polymorpha</i> <i>Marchantia paleacea</i>	(97) (34) (666) (487) (624) (459) (911) (971) (967) (840) (624) (760)	Plagiochin E Plagiochin E
1568	Riccardin F	$\text{C}_{29}\text{H}_{26}\text{O}_4$					
1569	Riccardin G	$\text{C}_{29}\text{H}_{26}\text{O}_4$					
1570	Riccardin H	$\text{C}_{31}\text{H}_{28}\text{O}_4$	227-228				
1571	Isoriccardin C	$\text{C}_{28}\text{H}_{24}\text{O}_4$					

(continued)

Table 4.6 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2 \text{ g}^{-1} 10^{-1}$	Plant source	References	Comments
					<i>Plagiochasma intermedium</i>	(967)	
1572	Isoriccardin D	$\text{C}_{28}\text{H}_{24}\text{O}_4$	251-252		<i>Plagiochasma rupestre</i>	(97)	
1573	Isoriccardinquinone A	$\text{C}_{29}\text{H}_{24}\text{O}_6$			<i>Marchantia polymorpha</i>	(210)	
1574	Isoriccardinquinone B	$\text{C}_{29}\text{H}_{24}\text{O}_5$			<i>Marchantia paleacea</i>	(760)	
1575	13,13'-O-Isopropylidenetricardin D	$\text{C}_{31}\text{H}_{28}\text{O}_4$	235-236		<i>Marchantia polymorpha</i>	(624)	
1576	Polymorphatin A	$\text{C}_{28}\text{H}_{24}\text{O}_4$	234-235		<i>Marchantia polymorpha</i>	(210)	
1577	Marchantin A	$\text{C}_{28}\text{H}_{24}\text{O}_5$	231-232		<i>Marchantia emarginata</i> subsp. <i>tosana</i>	(347)	
					<i>Marchantia paleacea</i> var. <i>diptera</i>	(794)	
					<i>Marchantia polymorpha</i>	(624)	
					<i>Plagiochasma</i> <i>appendiculatum</i>	(861)	
1578	Marchantin B	$\text{C}_{28}\text{H}_{24}\text{O}_6$	237-238		<i>Marchantia paleacea</i> var. <i>diptera</i>	(436)	
					<i>Marchantia polymorpha</i>	(760)	
					<i>Plagiochasma</i> <i>appendiculatum</i>	(624)	
					<i>Plagiochasma rupestre</i>	(97)	
1579	Marchantin C	$\text{C}_{28}\text{H}_{24}\text{O}_4$			<i>Dumortiera hirsuta</i>	(861)	
						(96)	
						(487)	
						(883)	
					<i>Jungermannia infusca</i>	(952)	
					<i>Marchantia foliacea</i>	(72)	
					<i>Marchantia paleacea</i> var. <i>diptera</i>	(347)	
						(436)	

				<i>Plagiochasma appendiculatum</i>	(760)
				<i>Plagiochila barteri</i>	(861)
					(295)
				<i>Schistochila glaucescens</i>	(607)
				<i>Reboulia hemisphaerica</i>	(712)
					(242)
					(935)
				<i>Riccardia nagasakiensis</i>	(141)
				<i>Marchantia polymorpha</i>	(436)
				<i>Marchantia paleacea</i> var. <i>diptera</i>	(794)
1580	Marchantin D	$C_{28}H_{24}O_6$		<i>Marchantia polymorpha</i>	(624)
1581	Marchantin E	$C_{29}H_{26}O_6$	144-146	<i>Marchantia polymorpha</i>	(436)
				<i>Asterella angusta</i>	(666)
1582	Marchantin G	$C_{28}H_{22}O_6$		<i>Plagiochasma intermedium</i>	(967)
1583	Marchantin H	$C_{28}H_{24}O_4$		<i>Plagiochila barteri</i>	(295)
				<i>Riccardia multifida</i> subsp. <i>decrescens</i>	(972)
1584	Marchantin I	$C_{29}H_{26}O_4$		<i>Marchantia polymorpha</i>	(210)
1585	Marchantin J	$C_{30}H_{28}O_6$		<i>Plagiochasma rupestre</i>	(97)
1586	Marchantin K	$C_{29}H_{26}O_7$		<i>Asterella angusta</i>	(666)
1587	Marchantin M	$C_{29}H_{26}O_5$		<i>Reboulia hemisphaerica</i>	(935)
				<i>Reboulia hemisphaerica</i>	(935)
1588	Marchantin N	$C_{29}H_{24}O_6$		<i>Reboulia hemisphaerica</i>	(935)
1589	Marchantiaquinone	$C_{28}H_{22}O_5$		<i>Mannia subpilosa</i>	(72)
					(436)
1590	Marchantin O	$C_{29}H_{26}O_4$		<i>Reboulia hemisphaerica</i>	(889)
					(935)
1591	Marchantin P	$C_{29}H_{26}O_4$		<i>Asterella angusta</i>	(666)

(continued)

Table 4.6 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}10^{-1}$	Plant source	References	Comments
1592	Isomarchantin C	$\text{C}_{28}\text{H}_{24}\text{O}_4$			<i>Marchantia chenopoda</i> <i>Marchantia foliacea</i> <i>Bryopteris filicina</i> <i>Dumortiera hirsuta</i> <i>Marchantia paleacea</i> var. <i>diptera</i>	(840) (347) (576) (883) (436)	X-ray
1593	Isomarchantin C 1'-methyl ether	$\text{C}_{29}\text{H}_{26}\text{O}_4$			<i>Marchantia foliacea</i>	(347)	
1594	Neoisomarchantin C	$\text{C}_{29}\text{H}_{26}\text{O}_4$			<i>Marchantia foliacea</i>	(347)	
1595	Neomarchantin A	$\text{C}_{28}\text{H}_{24}\text{O}_4$	224-225		<i>Marchantia polymorpha</i> <i>Plagiochasma intermedium</i> <i>Preissia quadrata</i> <i>Schistochila glaucescens</i>	(624) (967) (74) (72) (607) (712)	
1596	Neomarchantin B	$\text{C}_{28}\text{H}_{24}\text{O}_5$			<i>Schistochila glaucescens</i>	(72) (712)	
1597	Asterellin A	$\text{C}_{28}\text{H}_{22}\text{O}_4$	203-204		<i>Asterella angusta</i>	(666)	X-ray
1598	Asterellin B	$\text{C}_{29}\text{H}_{24}\text{O}_4$	196-197		<i>Asterella angusta</i>	(666)	
1599	11-O-Demethylmarchantin I	$\text{C}_{28}\text{H}_{24}\text{O}_4$	200-202		<i>Asterella angusta</i>	(666)	
1600	Dihydroptychantol A	$\text{C}_{28}\text{H}_{24}\text{O}_4$	201-202		<i>Asterella angusta</i>	(666)	
1601	Pakyonol	$\text{C}_{29}\text{H}_{26}\text{O}_4$			<i>Plagiochasma intermedium</i>	(924) (967) (314)	
1602	Planusin A	$\text{C}_{28}\text{H}_{22}\text{O}_4$			<i>Plagiochasma pterospermum</i>		Cell culture
1603	Plagiochin D	$\text{C}_{29}\text{H}_{26}\text{O}_4$			<i>Heteroscyphus planus</i> <i>Plagiochila ovalifolia</i>	(564) (701)	

					Cell culture
1604	Isoplagiochin A	$C_{28}H_{22}O_4$			(564) <i>Heteroscyphus planus</i> (330) <i>Plagiochila diversifolia</i> (313) <i>Plagiochila fruticosa</i> (553) (33) <i>Plagiochila permista</i> var. <i>integerrima</i> (313) <i>Plagiochila fruticosa</i> (553) (321) <i>Herbertus sakuraii</i> (323) (365) (714) (313) (34) (715) (321) (323) (365) (747) (313) (34) (33)
1605	Isoplagiochin B	$C_{28}H_{22}O_5$			
1606	Isoplagiochin C	$C_{28}H_{22}O_4$	+74.8		
1607	Isoplagiochin D	$C_{28}H_{24}O_4$	+42.5		
1608	Isoplagiochin E	$C_{28}H_{24}O_4$	+47.5		
1609	Isoplagiochin F	$C_{28}H_{24}O_5$			(323) (365) <i>Lepidozia fauriana</i> (747) <i>Plagiochila fruticosa</i> (313) <i>Plagiochila</i> sp. (34) <i>Plagiochila permista</i> var. <i>integerrima</i> (33) <i>Plagiochila permista</i> var. <i>integerrima</i> (33) <i>Plagiochila</i> sp. (34) <i>Plagiochila</i> sp. (34) <i>Bazzania tricrenata</i> (84)
1610	Isoplagiochin G	$C_{35}H_{26}O_7$			
1611	2',10',12,14'-Pentachloro-7',8'-dehydroisoplagiochin D	$C_{28}H_{17}O_4Cl_5$			
1612	12-Chloroisoplagiochin D	$C_{28}H_{23}O_4Cl$			

(continued)

Table 4.6 (continued)

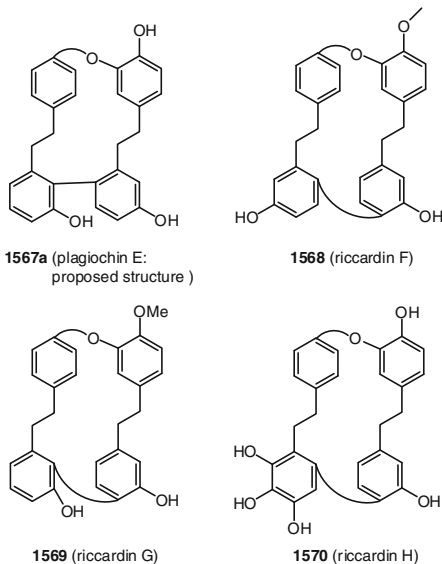
Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}10^{-1}$	Plant source	References	Comments
1613	2,12-Dichloroisoplagiochin D	$\text{C}_{28}\text{H}_{22}\text{O}_4\text{Cl}_2$	172-175	± 0	<i>Mastigophora dicladus</i> <i>Plagiochila permista</i> var. <i>integerrima</i> <i>Herbertus sakuraii</i>	(321) (33) (321) (323) (365)	
1614	12,7'-Dichloroisoplagiochin D	$\text{C}_{28}\text{H}_{22}\text{O}_4\text{Cl}_2$	140-143	-2.7	<i>Mastigophora dicladus</i> <i>Herbertus sakuraii</i>	(321) (321) (323) (365)	
1615	12,10'-Dichloroisoplagiochin C	$\text{C}_{28}\text{H}_{20}\text{O}_4\text{Cl}_2$		-19.1	<i>Herbertus sakuraii</i>	(321) (323) (365)	
1616	Bazzanin A	$\text{C}_{28}\text{H}_{21}\text{O}_4\text{Cl}$		+53.3	<i>Bazzania trilobata</i>	(522)	
1617	Bazzanin B	$\text{C}_{28}\text{H}_{20}\text{O}_4\text{Cl}_2$		+66.0	<i>Bazzania trilobata</i>	(522)	
1618	Bazzanin C	$\text{C}_{28}\text{H}_{19}\text{O}_4\text{Cl}_3$		+61.1	<i>Bazzania trilobata</i>	(715)	
1619	Bazzanin D	$\text{C}_{28}\text{H}_{19}\text{O}_4\text{Cl}_3$		+74.4	<i>Bazzania trilobata</i>	(522)	
1620	Bazzanin E	$\text{C}_{28}\text{H}_{18}\text{O}_4\text{Cl}_4$		+190.0	<i>Bazzania trilobata</i>	(522)	
1621	Bazzanin F	$\text{C}_{28}\text{H}_{18}\text{O}_4\text{Cl}_4$		+125.0	<i>Bazzania trilobata</i>	(522)	
1622	Bazzanin G	$\text{C}_{28}\text{H}_{17}\text{O}_4\text{Cl}_5$		+40.0	<i>Bazzania trilobata</i>	(522)	
1623	Bazzanin H	$\text{C}_{28}\text{H}_{17}\text{O}_4\text{Cl}_5$		+130.0	<i>Bazzania trilobata</i>	(522)	
1624	Bazzanin I	$\text{C}_{28}\text{H}_{16}\text{O}_4\text{Cl}_6$		+60.0	<i>Bazzania trilobata</i>	(522)	
1625	Bazzanin J	$\text{C}_{28}\text{H}_{22}\text{O}_4\text{Cl}_2$		+0.0	<i>Bazzania trilobata</i>	(522)	
1626	Bazzanin K	$\text{C}_{28}\text{H}_{20}\text{O}_4\text{Cl}_2$		+180.0	<i>Bazzania trilobata</i>	(522)	
1627	Bazzanin L	$\text{C}_{29}\text{H}_{21}\text{O}_4\text{Cl}_3$		+126.5	<i>Lepidozia incurvata</i>	(714)	

1628	Bazzanin M	$C_{28}H_{19}O_4Cl_3$	+95	<i>Lepidozia incurvata</i>	(714)
1629	Bazzanin N	$C_{28}H_{18}O_4Cl_4$	+90	<i>Lepidozia incurvata</i>	(714)
1630	Bazzanin O	$C_{29}H_{18}O_4Cl_5$	+54	<i>Lepidozia incurvata</i>	(714)
1631	Bazzanin P	$C_{28}H_{17}O_4Cl_5$	+225	<i>Lepidozia incurvata</i>	(714)
1632	Bazzanin Q	$C_{28}H_{16}O_4Cl_6$	+120	<i>Lepidozia incurvata</i>	(714)
1633	Bazzanin R	$C_{28}H_{14}O_4Cl_8$		<i>Lepidozia incurvata</i>	(714)
1634	Bazzanin S	$C_{28}H_{23}O_4Cl$	+1.1	<i>Bazzania trilobata</i>	(715)
1635	Plagilin	$C_{30}H_{30}O_6$		<i>Plagiochila</i> sp.	(716)
1636	Isoplagin	$C_{30}H_{30}O_6$		<i>Plagiochila</i> sp.	(34)
1637	Plagiolin	$C_{30}H_{30}O_6$		<i>Plagiochila</i> sp.	(34)
1638	Perrottetin E	$C_{28}H_{26}O_4$		<i>Asterella angusta</i>	(666)
				<i>Frullania convoluta</i>	(226)
				<i>Jungermannia comata</i>	(583)
				<i>Jungermannia infusca</i>	(584)
					(587)
				<i>Marchantia polymorpha</i>	(210)
				<i>Monoclea forsteri</i>	(635)
				<i>Nardia subclavata</i>	(84)
				<i>Pellia epiphylla</i>	(175)
					(182)
				<i>Radula laxiramea</i>	(178)
1639	Perrottetin F	$C_{28}H_{26}O_5$		<i>Frullania convoluta</i>	(226)
1640	Perrottetin G	$C_{29}H_{28}O_5$		<i>Frullania convoluta</i>	(226)
1641	7', 8'-Dehydroperrottetin F	$C_{28}H_{24}O_4$		<i>Frullania convoluta</i>	(226)
1642	Perrottetin E 11'-methyl ether	$C_{29}H_{28}O_4$		<i>Nardia cubclavata</i>	(84)
				<i>Pellia epiphylla</i>	(84)
1643	6,6', 10, 10', 12, 12'-Hexachloro-isoperrottetin A	$C_{28}H_{20}O_4Cl_6$	+0.0	<i>Jamesoniella colorata</i>	(340)

(continued)

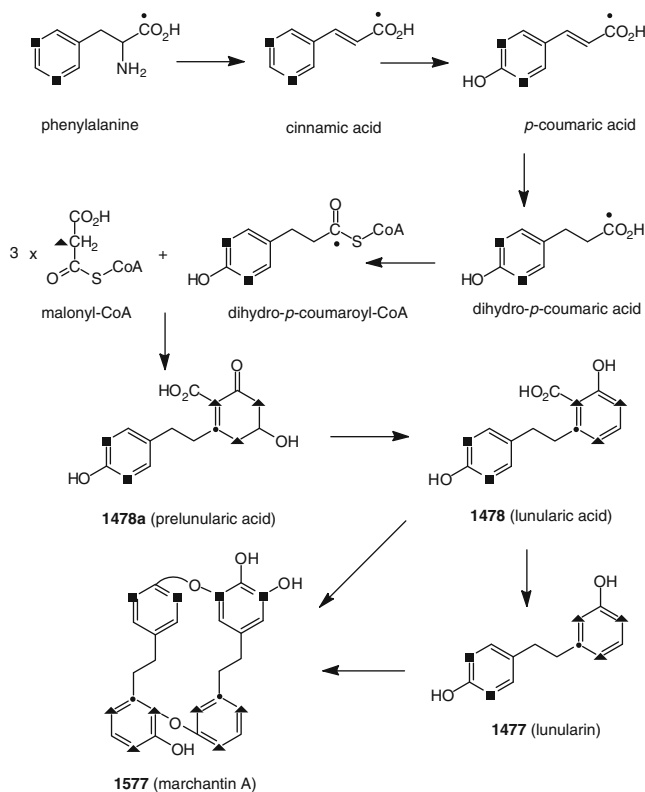
Table 4.6 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source	References	Comments
1644	Perrottetin E-11-methyl ether	$\text{C}_{29}\text{H}_{28}\text{O}_4$			<i>Pellia epiphylla</i>	(182)	
1645	14'-Hydroxyperrottetin E	$\text{C}_{28}\text{H}_{26}\text{O}_5$			<i>Pellia epiphylla</i>	(182)	sporophyte
1646	10'-Hydroxyperrottetin E	$\text{C}_{28}\text{H}_{26}\text{O}_5$			<i>Pellia epiphylla</i>	(175)	
1647	10'-Hydroxyperrottetin E-11-methyl ether	$\text{C}_{29}\text{H}_{28}\text{O}_5$			<i>Pellia epiphylla</i>	(182)	sporophyte
1648	10,10'-Dihydroxyperrottetin E	$\text{C}_{28}\text{H}_{26}\text{O}_6$			<i>Pellia epiphylla</i>	(182)	
1649	Ptychantol A	$\text{C}_{28}\text{H}_{22}\text{O}_4$	260-262	± 0	<i>Ptychanthus striatus</i>	(320)	X-ray
1650	Ptychantol B	$\text{C}_{28}\text{H}_{22}\text{O}_5$	235-237	± 0	<i>Ptychanthus striatus</i>	(320)	
1651	Ptychantol C	$\text{C}_{28}\text{H}_{22}\text{O}_5$	155-158	-14.8	<i>Ptychanthus striatus</i>	(320)	
1652	Pusilatin A	$\text{C}_{56}\text{H}_{46}\text{O}_8$			<i>Blasia pusilla</i>	(971)	
1653	Pusilatin B (=6',6'''-Bisriccardin C)	$\text{C}_{56}\text{H}_{46}\text{O}_8$			<i>Blasia pusilla</i>	(971)	
1654	Pusilatin C	$\text{C}_{56}\text{H}_{46}\text{O}_8$			<i>Ricciocarpos natans</i>	(453)	
1655	Pusilatin D	$\text{C}_{56}\text{H}_{46}\text{O}_8$			<i>Blasia pusilla</i>	(971)	
1656	Pusilatin E	$\text{C}_{58}\text{H}_{50}\text{O}_8$	195-196		<i>Blasia pusilla</i>	(971)	
1657	13',13'''-bis(10'-Hydroxyperrottetin E)	$\text{C}_{56}\text{H}_{50}\text{O}_{10}$			<i>Riccardia multifida</i> subsp. <i>decrescens</i>	(972)	
1658	GBB A (Glaucescens bisbibenzyl A)	$\text{C}_{43}\text{H}_{44}\text{O}_6$		+20	<i>Pellia epiphylla</i>	(182)	
1659	GBB B (Glaucescens bisbibenzyl B)	$\text{C}_{43}\text{H}_{44}\text{O}_6$		+26	<i>Schistochila glaucescens</i>	(607)	
					<i>Schistochila glaucescens</i>	(712)	
					<i>Schistochila glaucescens</i>	(607)	
					<i>Schistochila glaucescens</i>	(712)	

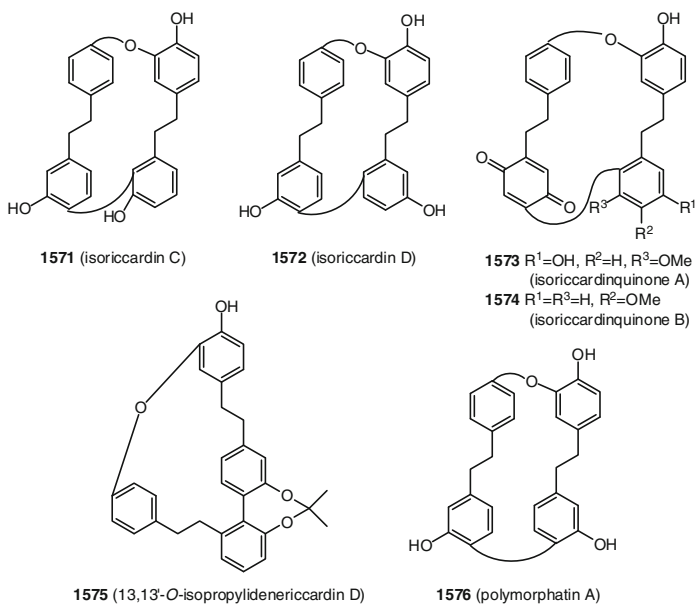


Bis-bibenzyls found in the Marchantiophyta

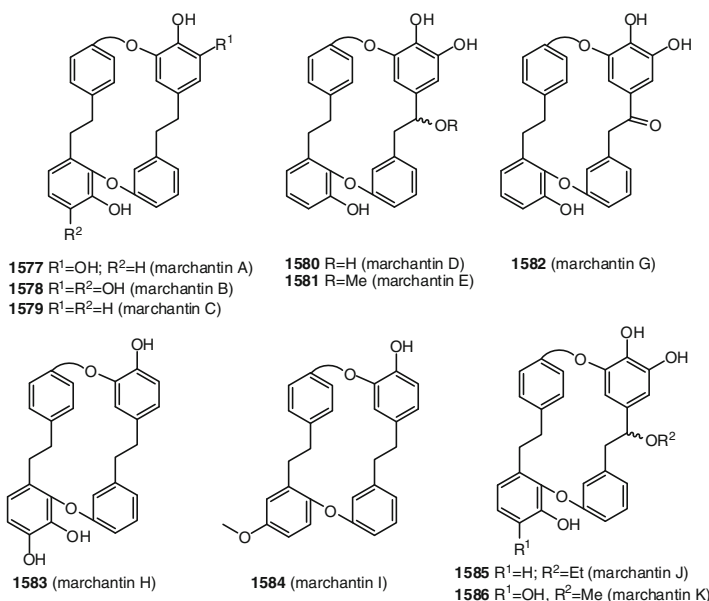
Asakawa and *Matsuda* proposed that cyclic bis-bibenzyls, such as riccardin C (**1566**) and marchantin A (**1577**), might be biosynthesized from bibenzyls that correspond chemically to dihydrostilbenes (**54**). This assumption was proved by feeding experiments using radioactive and ^{13}C -labelled precursors, like L-[$U\text{-}^{14}\text{C}$] phenylalanine, [$U\text{-}^{14}\text{C}$]dihydro-*p*-coumaric acid, [$2\text{-}^{13}\text{C}$]acetate, and L-[^{13}C COOH] phenylalanine, as shown in Scheme 4.51 (231, 232). The aqueous precursor solutions were applied to 0.5 cm² samples of aseptic thallus tissue of *Marchantia polymorpha* and incubated for 24 h. The A- and B-rings of the marchantin molecule are derived from the benzene ring of L-phenylalanine via *trans*-cinnamic acid and *p*-coumaric acid. Application of the ^{13}C -labeled precursor with subsequent ^{13}C NMR spectroscopy established that dihydrocoumaric acid is an intermediate in marchantin biosynthesis. Enzymatically hydrogenated dihydrocoumaric acid from coumaric acid condenses with three molecules of malonyl-CoA to form prelunularic acid (**1478a**). The latter is aromatized to yield lunularic acid (**1478**) and possibly lunularin (**1477**), which is followed by condensation of lunularin or lunularic acid to afford marchantin A (**1577**). The mechanism of this final coupling step is still unknown.



Scheme 4.51 Biosynthesis pathways to marchantin A (1577)



Bis-benzyls found in the Marchantiophyta



Bis-bibenzylls found in the Marchantiophyta

Since cyclic bis-bibenzylls found in liverworts possess unusual structures and various interesting biological activities, several organic chemists have focused on their total synthesis. *Gottsegen* and colleagues synthesized riccardins A–C (**1564–1566**) using a combination of *Ullmann*, *Wittig*, and *Wurtz* reactions and Ni (0)-assisted intermolecular coupling reaction (262). The total synthesis of riccardin C (**1566**) was also accomplished by *Harrowven* and associates using isovanillin as the starting material in the course of the total synthesis of cavicularin (**1560**), as shown in Scheme 4.50 (301). The total synthesis of riccardin C (**1566**), which possesses nuclear receptor LXR α selective agonist activity (see Chap. 7), and seven *O*-methylated derivatives, were achieved by *Hioki* and coworkers via intramolecular *Suzuki-Miyaura* coupling to construct the necessary 18-membered biaryl linkage (342).

A mixture of the ether and methanol extracts of *Preissia quadrata* was purified by means of column chromatography on Sephadex LH-20 to give riccardin B (**1565**) and neomarchantin A (**1595**) (74). This was the first example of the isolation of neomarchantin A (**1595**) from a thalloid liverwort, although it was isolated from the leafy liverwort *Schistochila glaucescens* (40).

Blasia pusilla elaborates not only the monomeric bis-bibenzylls, riccardin C (**1566**) and riccardin F (**1568**) (971), but also the bis-bibenzyll dimers, pusilatins A–D (**1652–1655**) (40, 971). The stereostructure of pusilatin A (**1652**) was established by X-ray crystallographic analysis (Fig. 4.22) of its hexaacetate (75, 971). The structure previously proposed for pusilatin D was revised to **1655** by

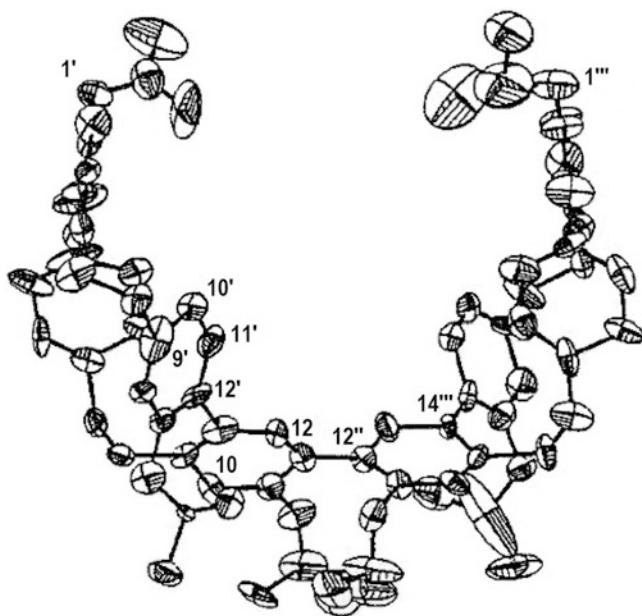


Fig. 4.22 ORTEP drawing of pusilatin A hexaacetate

detailed analysis of its ^1H - ^1H COSY, HOHAHA, HSQC, and HMBC NMR spectra (971). Pusilatin B (1653) has also been found in the axenic cultured liverwort *Ricciocarpos natans*, belonging to the Ricciaceae (453). While *Riccardia multifida* subsp. *decrescens*, *Blasia pusilla*, and *R. natans* are different morphologically from one another, they are chemically very similar.

Fractionation of the methanol extract of *Riccardia multifida* subsp. *decrescens* resulted in the isolation of the new bis-bibenzyl dimer pusilatin E (1656), together with riccardin A (1564) and marchantin I (1584). The structure of 1656 was elucidated as the C-6'/C-6'''-coupled symmetrical dimer of riccardin A (1564) using a combination of its FABMS and 2D-NMR spectroscopic data. Methylation of 1564 gave a trimethoxy derivative for which the chromatographic behavior and spectra were similar to those of pusilatin B (1653) hexamethyl ether (972). Further evidence for the structure of 1656 was obtained by its partial synthesis from riccardin A (1564). Oxidative coupling of 1564 in ethanol with manganese triacetate gave a C-6'/C-6'''-coupled symmetrical dimer having spectroscopic data identical to those of the natural product (1656). Furthermore, the demethylation of 1656 with boron tribromide gave the naturally occurring pusilatin B (1653) (972).

Marchantin A (1577) was reacted with *m*-chloroperbenzoic acid to give 2- and 5'-hydroxymarchantin A as well as the C-ring cleaved muconate and its 4'-oxo derivative (851, 853).

Plagiochin E (1567a) was isolated from the Chinese *Marchantia polymorpha* (624) and *Asterella angusta* (666) through bioassay-guided fractionation of the

antifungal constituents. A short and efficient total synthesis of plagiochin E (**1567a**) was accomplished by *Speicher* and associates (769). However, its spectroscopic data were not the same as those of the natural product **1567a**, but identical with those of riccardin D (**1567**), which was isolated from *Plagiochila fruticosa* (40). Thus, the structure of **1567a** should be revised as riccardin D (**1567**). Riccardin G (**1569**), the methyl ether of **1567**, has been found in *Marchantia chenopoda* (40).

So and colleagues reported that *Marchantia paleacea* from Hong Kong produces two new bis-bibenzyl quinones, named isoriccardinquinones A (**1573**) and B (**1574**), for which their structures were determined mainly by means of the interpretation of spectroscopic data, including DEPT and HMBC NMR experiments (760).

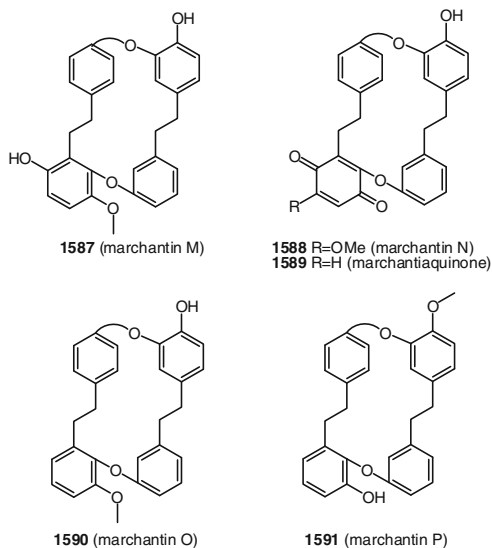
From the ether extract of the Chinese *Marchantia polymorpha*, two additional bis-bibenzyls, isoriccardin D (**1572**) and polymorphatin A (**1576**), were isolated as minor components, and were obtained together with marchantin J (**1585**) and perrottetin E (**1638**) (210). The structures of **1572** and **1576** were deduced using HRMS and 2D-NMR experiments, inclusive of the HMQC and HMBC spectroscopic correlations.

Marchantia polymorpha is known to produce a large amount of the macrocyclic bis-bibenzyl, marchantin A (**1577**) and its analogues (39, 40). *Niu* and associates re-investigated the same Chinese species and found the presence of the three new bis-bibenzyls, 13,1',13'-trihydroxyplagiochin (13,13'-*O*-isopropylidenericcardin D) (**1575**), 10,11,12,1',13'-pentahydroxyriccardin (riccardin H) (**1570**), and plagiochin E (**1567a**), together with marchantin A (**1577**), marchantin B (**1578**), marchantin E (**1581**), and neomarchantin A (**1595**) (624). The structures of the new bis-bibenzyls were elucidated by 2D-NMR methods, especially using their HMBC and NOESY experiments.

The ether extract of the New Zealand *Marchantia berteroana* was purified by column chromatography to afford not only δ -cuparenol (**483**) (40), but also marchantin C (**1579**) (616). This was the first report of the isolation of the macrocyclic bis-bibenzyls in a *Marchantia* species collected in New Zealand. Further investigation of the methanol extract of *Marchantia polymorpha* led to the isolation of marchantins A (**1577**), D (**1580**), E (**1581**), and G (**1582**) (436). Previously, the structure of marchantin G (**1582**) was determined only by spectroscopic data interpretation. The stereostructure of **1582** was established conclusively by X-ray crystallographic analysis of its permethylated derivative. Marchantin A (**1577**) is not stable in chloroform solution and gives an unknown dimer (m/z 878, $[M]^+$). When marchantin D (**1580**) was purified by chromatography on a CN Lobar column using methanol for elution, the original compound disappeared and, in its place, marchantin E (**1581**) was obtained. When marchantin D (**1580**) was dissolved in methanol and allowed to stand for a day, marchantin E (**1581**) was also formed. Thus, marchantin E, which was isolated from the natural source, is a methanolysis artifact from marchantin D (**1580**) (84, 436). Marchantin C (**1579**) and marchantin H (**1583**) have been isolated from the ether extract of *Plagiochila barteri* (295). The distribution of marchantin-type bis-bibenzyls in the Plagiochilaceae is very rare although isoplagiochin-type bis-bibenzyls occur in this family (40). Further

investigation of the ether extract of *Marchantia paleacea* var. *diptera* (Fig. 4.23), collected in a different location, led to the isolation of marchantins A (**1577**) and C (**1579**), and isomarchantin C (**1592**) (436, 877).

Bardón and colleagues reported the isolation of four macrocyclic bis-bibenzylys, riccardin C (**1566**), isoriccardin C (**1571**), marchantin B (**1578**), and marchantin K (**1586**) from the ether and methanol extracts of the Argentinean *Plagiochasma rupestre* (97). In previous work, no bis-bibenzylys were found in *Dumortiera hirsuta* (40). Further fractionation of the ether extract of the Japanese *D. hirsuta* resulted in the isolation of riccardin C (**1566**), marchantin C (**1579**), and isomarchantin C (**1592**) (883). Marchantin C (**1579**) also occurred in the Argentinean *Dumortiera hirsuta* (Fig. 4.24) (96). The structure of isomarchantin C (**1592**) isolated from the Indian *Marchantia polymorpha* and *M. palmata* was assigned initially using spectroscopic methods (40). Conclusive evidence for the structure of **1592** was obtained later by X-ray crystallographic analysis (883).



Bis-bibenzylys found in the Marchantiophyta

The ethyl acetate extract of the Taiwanese *Reboulia hemisphaerica* was purified by column chromatography to give the two new marchantins M (**1587**) and N (**1588**), along with known marchantiaquinone (**1590**), marchantin C (**1579**), and marchantin O (**1589**). The structures of **1587** and **1588** were assigned by interpretation of their ^1H , ^{13}C , and HMBC NMR spectroscopic data and comparison with the analogous values for marchantiaquinone (**1590**) and marchantin C (**1579**) (935). Marchantin C (**1579**), marchantin O (**1589**), and marchantiaquinone (**1590**) were also isolated from newly collected Japanese *Reboulia hemisphaerica* (436, 889). The latter was found in *Mannia subpilosa* (40).



Fig. 4.23 *Marchantia paleacea* var. *diptera*

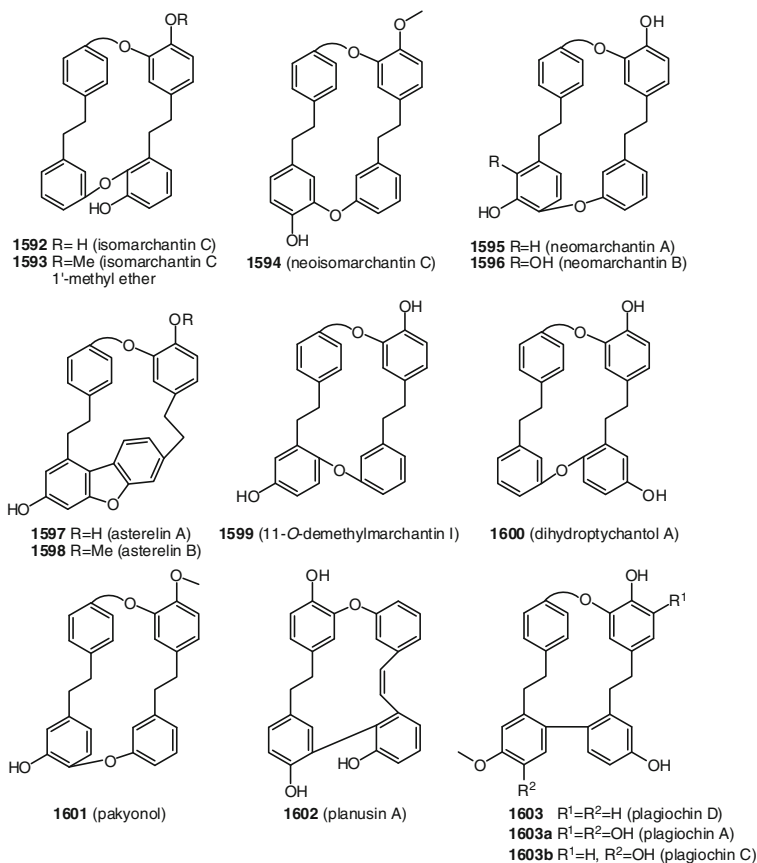


Fig. 4.24 *Dumortiera hirsuta*

Xi and associates accomplished the total synthesis of marchantin C (**1579**) by 12 steps from 2-hydroxy-3-methoxybenzaldehyde in sufficient yield (23%) (965). The total synthesis of marchantiaquinone (**1590**) was accomplished by *López* and associates by macro-cyclization from a dichloride precursor using an active nickel complex under high dilution conditions, giving marchantin M (**1587**) trimethyl ether, followed by demethylation with boron tribromide and oxidation using silver oxide (480).

Mombrú and colleagues studied the conformation of marchantin M (**1587**) trimethyl ether by X-ray crystallographic analysis (548). The structure of this trimethyl ether includes two intramolecular $C_8-H_7 \cdots C_{14,11}O$ and $C_7-H_7 \cdots C_{10}OMe$

close contacts, which may stabilize in part the observed conformation. An extremely high chemical shift at δ_{H} 5.49 ppm for H-3' was observed in this molecule. This phenomenon ($\delta_{\text{H}3'}$ 5.33 ppm in riccardin A (**1564**) and 5.11 ppm in marchantin A (**1577**)) has already been explained in regard to the conformation of compounds in the riccardin A and marchantin A series by *Asakawa* and his coworkers ([56](#), [797](#)).



Bis-benzyls found in the Marchantiophyta

Previously, the New Zealand *Marchantia foliacea* was analyzed chemically and several cadinanes and germacrene D were identified ([40](#)). The ether extract of the same species was reinvestigated to give the two new bis-benzyls **1593** and **1594**, together with the known marchantin C (**1579**), isomarchantin C (**1592**), and marchantin P (**1591**) ([347](#)). The structure of **1592** was confirmed as a result of X-ray crystallographic analysis. The ^1H and ^{13}C NMR spectra of **1593** resembled those of isomarchantin C (**1592**), except for evidence for the presence of a methoxy group in place of a phenolic hydroxy group, indicating **1593** to be methoxyisomarchantin C 1'-methyl ether. This was confirmed by the formation of isomarchantin C-1',13'-

dimethyl ether from **1593** and isomarchantin C (**1592**) by methylation with methyl iodide. The positions of one methoxy group of **1592** and two methoxy groups of **1593** were confirmed by NOESY experiments and MOE (Molecular Operating Environment, version 2002.03, Chemical Computing Group KK) calculations carried out on both compounds. Thus, the structure of **1593** was established as isomarchantin C-1'-methyl ether. Compound **1594**, named neoisomarchantin C, possesses the same molecular formula as determined by HRMS. Its ^1H and ^{13}C NMR and 2D NMR spectroscopic data indicated that **1594** has the same A- and C-ring substituents with two benzylic groups. Supporting evidence for the structure of **1594** was arrived at by the careful analysis of the 2D-NMR (COSY, HMBC, and NOESY) data of the B and D ring regions of the molecule (347).

Tori and coworkers reported the isolation and structure elucidation of marchantin H (**1583**) from *Plagiochasma intermedium* (836). This same species collected in China elaborates pakyonol (**1601**) (924, 967), along with riccardin C (**1566**), riccardin F (**1568**), isoriccardin C (**1571**), and neomarchantin A (**1595**) (967). The plant name *Plagiochasma intermedlum* mentioned in the above paper should be revised to *Plagiochasma intermedium*.

Plagiochasma pterospermum produces riccardin C (**1566**) and pakyonol (**1601**) (314). Lahlou and colleagues reported that the methanol extract of *Plagiochasma japonica* contains riccardin D (**1567**) (459). Nogradi and associates accomplished the total synthesis of pakyonol (**1601**) by Ullmann coupling of 3-benzoyloxy-4-(3-formylphenoxy)benzoic acid benzyl ester with Wittig and modified Wittig reactions (625).

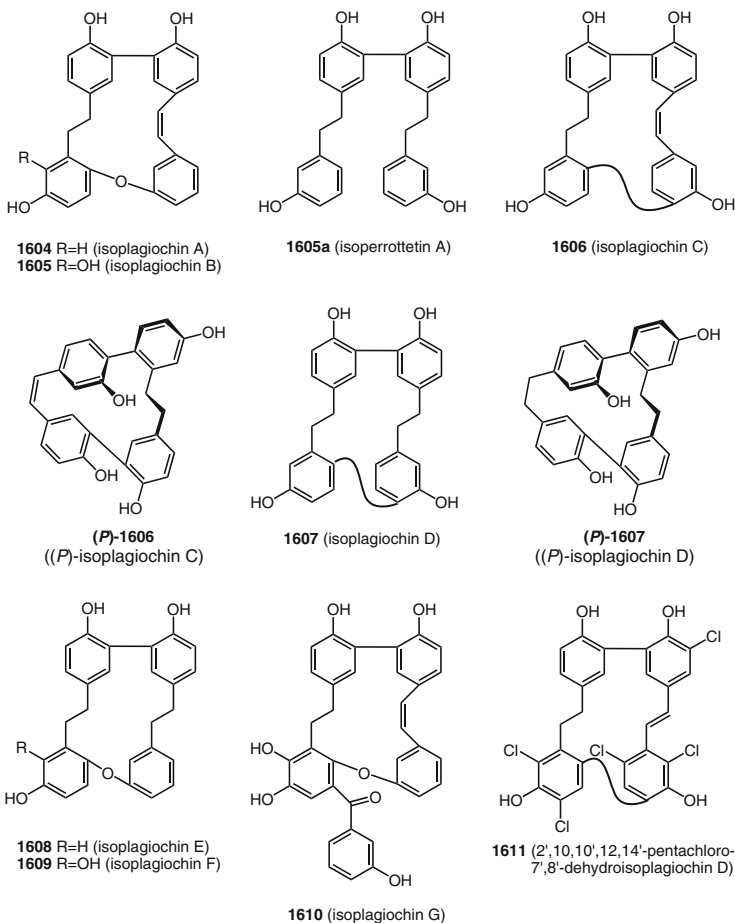
The genus *Asterella* belongs to the Aytoniaceae and there are about 80 species worldwide. Qu and coworkers used TLC bioautography for the detection of antifungal active compounds in the Chinese *Asterella angusta* and found the presence of four new bis-bibenzylys, asterellin A (**1597**), asterellin B (**1598**), 11-*O*-demethylmarchantin I (**1599**), and dihydroptychantol A (**1600**), together with the known macrocyclic bis-bibenzylys, marchantin H (**1583**), marchantin M (**1587**), marchantin P (**1591**), perrottetin E (**1638**), riccardin B (**1565**), and riccardin D (**1567**) (666). These structures of the new compounds were established by a combination of 2D-NMR and/or X-ray crystallographic data analysis as well as by comparison with reference values mainly established by Asakawa and his group (40, 75). Bioactivity-guided fractionation of the ether extract of *Plagiochila ovalifolia* using a DHHP radical-scavenging assay resulted in the isolation of plagiochin D (**1603**) (701).

Fukuyama and associates accomplished the total synthesis of plagiochin D (**1603**) using *m*-anisaldehyde as the starting material, followed by a Wardworth-Emmons condensation reaction, hydrogenation, and a Still-Kelly reaction using hexamethylditin and tetrakis(triphenylphosphine)palladium, to yield plagiochin D (**1603**), after removal of the MOM group by HBr in methanol (239).

A methanol extract of the cultured cells and gametophytes of *Heteroscyphus planus* was fractionated by HPLC to give the new bis-bibenzyl planusin (**1602**) together with the known isoplagiochin A (**1605**). The arrangement of the substituents on the four benzene rings of planusin (**1602**) was established by a combination of HMBC and NOE experiments. The ether linkage between C-6

and C-2' was assigned as the sole ether linkage by taking into account the steric distortion of the molecule (564).

The total synthesis of isoplagiochin A (1604) was achieved by Gerencsér and colleagues in 23 steps by coupling methyl 3-(2-methoxy-5-formylphenyl)-4-methoxybenzoate with methyl (2-(hydroxymethyl)-4-methoxyphenoxy)benzoate, in an overall yield of 15% (254).

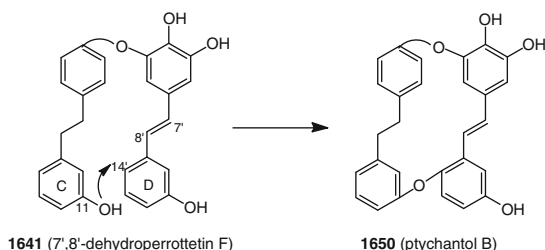


Bis-bibenzyIs found in the Marchantiophyta

Previously, the two novel macrocyclic bis-bibenzyIs, isoplagiochins A (1604) and B (1605) were isolated from the methanol extract of the Japanese *Plagiochila fruticosa* (40). Later fractionation of a methanol extract of this same liverwort led to the isolation of two novel macrocyclic bis-bibenzyIs named isoplagiochin C (1606) and isoplagiochin D (1607), for which the spectroscopic data were similar to those of isoplagiochin A (1604) except for evidence for the presence of a (Z)-double bond (δ_{H} 6.55 and 6.65 ppm, $J = 11.5$

Hz, H-7', H-8'; UV 287 nm), and a signal pattern of the D-ring indicating that compound **1606** possesses two biphenyl linkages with one stilbene moiety and four phenolic hydroxy groups. This was confirmed by the preparation of the tetraacetate by acetylation. The whole structure was determined on the basis of COSY, HMBC, HMQC and NOESY experiments. Isoplagiochin D (**1607**) has spectroscopic data very similar to those of **1606** except for the presence of four methylene signals. Acetylation and methylation of **1607** gave the tetraacetate and tetramethyl ether, suggesting the presence of four phenolic hydroxy groups. Hydrogenation of the tetraacetate of **1606** afforded a dihydro derivative with spectroscopic data identical with those of the tetraacetate of **1607**. Thus, the structure of **1607** was established as dihydroisoplagiochin C. Isoplagiochins A (**1604**) and B (**1605**) possess a C-14-C-11' ether linkage and a C-6-C-2' biphenyl bond, whereas isoplagiochins C (**1606**) and D (**1607**) have two C-6-C-2' and C-14-C12' biphenyl bonds. Isoplagiochins A-D (**1604**–**1607**) may be biosynthesized from isoperrottetin A (**1605a**), isolated from the liverwort *Radula perrottetii* (40). The latter was formed by dimerization of lunularin (**1477**) found in most of the liverworts, as shown in Scheme 4.52 for ptychanol B (**1650**). This is the first report of the isolation of macrocyclic bis-bibenzylys possessing two biphenyl linkages between rings A and C/rings B and D (313).

It is considered that the halogenated bis-bibenzylys might be artifacts originating from isoplagiochin C (**1606**) and isoplagiochin D (**1607**), which tend to co-exist in *H. sakurarii* during chromatographic work up. To exclude this hypothesis, **1606** and **1607** were dissolved in a mixture of chloroform and methanol, Sephadex LH-20 was added, and then reflux was carried out for 4 h. As a result, the starting materials were recovered and no halogenated compounds were detected. Thus, the new chlorinated compounds are real natural products. *Speicher* and colleagues found that the chlorinated bis-bibenzylys did not constitute artifacts of extraction because they were directly detected by MALDI-TOF mass spectrometry (768). It was confirmed that chlorinated bis-bibenzylys are biosynthesized by a chloroperoxidase from *Caldariomyces fumago* in KCl or KBr and hydrogen peroxide at pH 3.0, and an enzyme of this type was detected in the liverwort, *Bazzania trilobata*, which produces a number of chlorinated bis-bibenzylys. This is the first discovery of a haloperoxidase from the liverworts (768). However, compounds **1606** and **1607** both showed a positive optical rotation ($[\alpha]_D +74.8^\circ \text{ cm}^2 \text{ g}^{-1} 10^{-1}$ for **1606**; and $+47^\circ \text{ cm}^2 \text{ g}^{-1} 10^{-1}$ for **1607**) and their *Cotton* effects were measured ($\lambda(\Delta\epsilon) = 231(+24.4), 213(-63.2)$ for **1606** and $252 (+2.4), 225 (+22.5) \text{ nm} (\text{mol}^{-1} \text{ dm}^3 \text{ cm}^{-1})$) for **1607**) (135). The separation of the enantiomers of isoplagiochin C (**1606**) and isoplagiochin D (**1607**) on a chiral phase HPLC provided enantiomers of almost all bis-bibenzylys isolated from *B. trilobata*. A direct stereochemical online analysis of the peaks by LC-CD coupling exhibited opposite CD curves, clearly revealing that the separated products are enantiomers but do not occur in a pure enantiomeric form in Nature. The assignment of these two peaks to the respective enantiomers was achieved by quantum chemical CD calculations using a molecular dynamics (MD) based approach. Isoplagiochin C (**1606**) and isoplagiochin D (**1607**) were not obtained



Scheme 4.52 Formation of ptychantol B from 7',8'-dehydroperrottetin F

enantiomerically pure, but occurred in a 85:15 and 48:52 ratio, respectively, in favor of the enantiomer possessing the (*P*)-configuration ((*P*)-**1606** and (*P*)-**1607**) at the stereochemically most stable axis. Racemization rates of isoplagiochin C (**1606**) were determined at different temperatures from 85°C to 145°C. From the corresponding *Arrhenius* plot, an activation energy of 101.6 kJ/mol for the racemization was calculated, in good accordance with the theoretically predicted value of 115.0 kJ/mol. This result led to the expectation of a molecule configurationally stable at room temperature. However, the specific optical rotation value varied even for the same compound depending on the plant source and the isolation procedure (715, 716). A decrease of the enantiomeric purity can occur during standard isolation methods at a temperature higher than 50°C.

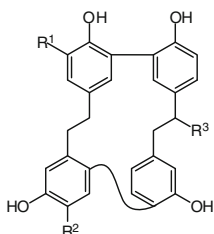
Further fractionation of the methylene chloride extract of *B. trilobata* led to the isolation of isoplagiochin D (**1607**) and 6'-chloroisoplagiochin D (named bazzanin S; **1634**) (715, 716). The latter compound was reported for the first time from a liverwort; however, earlier it was obtained as a derivative in the total synthesis of bazzanin A (**1616**) (767).

From the ethyl acetate extract of the Taiwanese *Lepidozia fauriana*, isoplagiochin D (**1607**) was isolated. This was the first isolation of a bis-biphenyl from this species, although members of the *Bazzania* genus belonging to the same family Lepidoziaceae produce a number of bis-biphenyls, as mentioned earlier (522, 747).

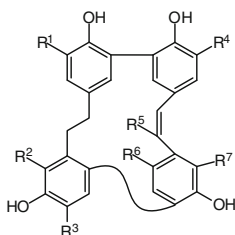
Eicher and associates established the total synthesis of isoplagiochin C (**1606**) (200). The total synthesis of isoplagiochin D (**1607**), a highly strained macrocyclic bis-biphenyl with two biaryl units isolated from *Plagiochila fruticosa*, was achieved by *Esumi* and colleagues in 1.6% overall yield and in 11 steps, by construction of tetramethoxyisoplagiochin D by a palladium(0)-catalyzed *Suzuki-Miyaura* cross-coupling reaction, followed by demethylation with boron tribromide in methylene chloride (208). The tetramethyl ether of isoplagiochin D (**1607**) as well as related compounds possessing the (*Z*)- and (*E*)-alkenes with more rigid two-carbon biaryl bridges, were synthesized using *Sonogashira* and *McMurry* protocols (770).

The dichloromethane extract of an unidentified Costa Rican *Plagiochila* species, later identified as *P. permista* var. *integerrima* (see (34)), was fractionated to afford not only phenanthrenes and biphenyls, but also the three new bis-biphenyls, isoplagiochin

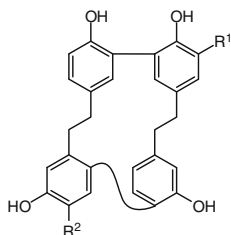
E (**1608**), isoplagiochin F (**1609**), and 12-chloro-isoplagiochin D (**1612**), together with the two known bis-bibenzyis, perrottetin E (**1638**) and isoplagiochin A (**1604**). The substitution patterns proposed in rings C and D of the new compounds **1608** and **1609** were based on a comparison of their 2D-NMR spectra with those of isoplagiochin A (**1604**). The presence of a chlorine atom was also confirmed by comparison of a combination of the mass spectrometric and NMR spectroscopic data with those of isoplagiochin D (**1607**) (**33**) isolated from *Plagiochila fruticosa* (**40**).



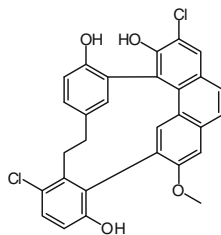
1612 $R^1=R^3=H$, $R^2=Cl$ (12-chloroisoplagiochin D)
1613 $R^1=R^2=Cl$, $R^3=H$ (2,12-dichloroisoplagiochin D)
1614 $R^1=H$, $R^2=R^3=Cl$ (12,7'-dichloroisoplagiochin D)



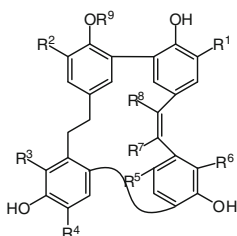
1615 $R^1=R^2=R^4=R^5=R^7=H$, $R^3=R^6=Cl$ (12,10'-dichloroisoplagiochin C)
1616 $R^1=R^2=R^3=R^5=R^6=R^7=H$, $R^4=Cl$ (bazzanin A)
1617 $R^1=R^2=R^3=R^6=R^7=H$, $R^4=R^5=Cl$ (bazzanin B)
1618 $R^1=R^2=R^6=R^7=H$, $R^3=R^4=R^5=Cl$ (bazzanin C)
1619 $R^1=R^2=R^3=R^7=H$, $R^4=R^5=R^6=Cl$ (bazzanin D)
1620 $R^1=R^2=R^7=H$, $R^3=R^4=R^5=R^6=Cl$ (bazzanin E)
1621 $R^1=R^3=R^6=H$, $R^2=R^4=R^5=R^7=Cl$ (bazzanin F)
1622 $R^3=R^7=H$, $R^1=R^2=R^4=R^5=R^6=Cl$ (bazzanin G)
1623 $R^1=R^3=H$, $R^2=R^4=R^5=R^6=R^7=Cl$ (bazzanin H)
1624 $R^2=H$, $R^1=R^3=R^4=R^5=R^6=R^7=Cl$ (bazzanin I)



1625 $R^1=R^2=Cl$ (bazzanin J)
1634 $R^1=Cl$, $R^2=H$ (bazzanin S)



1626 (bazzanin K)



1627 $R^1=R^2=R^6=R^7=R^8=H$, $R^3=R^4=R^5=Cl$, $R^9=Me$ (bazzanin L)
1628 $R^1=R^2=R^6=R^7=R^8=R^9=H$, $R^3=R^4=R^5=Cl$ (bazzanin M)
1629 $R^1=R^6=R^7=R^8=R^9=H$, $R^2=R^3=R^4=R^5=Cl$ (bazzanin N)
1630 $R^2=R^7=R^8=H$, $R^1=R^3=R^4=R^5=R^6=Cl$, $R^9=Me$ (bazzanin O)
1631 $R^1=R^2=R^3=R^4=R^5=Cl$, $R^6=R^7=R^8=R^9=H$ (bazzanin P)
1632 $R^1=R^2=R^3=R^4=R^5=R^6=Cl$, $R^7=R^8=R^9=H$ (bazzanin Q)
1633 $R^1=R^2=R^3=R^4=R^5=R^6=R^7=R^8=Cl$, $R^9=H$ (bazzanin R)

Chlorinated bis-bibenzyis found in the Marchantiophyta

The ether and ethyl acetate extracts of the Japanese primitive stem-leafy liverwort *Herbertus sakuraii* (Herbertaceae) were found to contain the two new optically active chlorinated compounds, (–)-12,7′-dichloroisoplagiochin D (**1614**) ($[\alpha]_D^{20} -2.7^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$; $\lambda(\Delta\epsilon) = 300(+0.74), 281(-0.39), 234(+5.34) \text{ nm} (\text{mol}^{-1} \text{dm}^3 \text{cm}^{-1})$) and (–)-12,10′-dichloroisoplagiochin C (**1615**) ($[\alpha]_D^{21} -19.1^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$; $\lambda(\Delta\epsilon) = 322(+7.80), 282(-7.47), 244(+48.08), 214(-157.72) \text{ nm} (\text{mol}^{-1} \text{dm}^3 \text{cm}^{-1})$), along with an optically inactive compound, 2,12-dichloroisoplagiochin D (**1613**) (321). These were obtained together with the two known optically active non-halogenated substances, isoplagiochin C (**1606**) and isoplagiochin D (**1607**), which have been isolated from the liverwort *Plagiochila fruticosa* (313). The structures of **1613–1615** were established by a combination of analysis of their spectroscopic data with those of isoplagiochins C and D, and/or X-ray crystallographic analysis. Compound **1613** was present in the racemic form since neither an optical rotation nor a Cotton effect could be observed. The bis-bibenzylys **1606** and **1607** showed a positive sign of optical rotation and a positive first Cotton effect in their CD spectra, indicating that both compounds are optically active. The chlorinated bis-bibenzylys have been found in the liverworts *Bazzania trilobata* (522) and *Plagiochila oresitropa* (33), as mentioned above. This was the third report of the isolation of chlorinated bis-bibenzylys from liverworts. Compound **1614** possesses planar chirality since it shows a negative optical rotation and positive, negative, and positive Cotton effects of their three absorption bands. Compound **1615** also showed the same chiroptical signals as mentioned above. However, it proved to be difficult to establish the absolute configuration of both **1614** and **1615** and the non-halogenated **1606** and **1607** from their CD spectra, because of the possibility of the presence of four atropisomers for each isolated compound (321).

Two optically inactive chlorinated bis-bibenzylys, 12-chloroisoplagiochin D (**1612**) and 2,12-dichloroisoplagiochin D (**1613**), also have been isolated from *Mastigophora diclados* along with the herbertanes, herbertene (**508**) and α -herbertenol (**509**). This was the first isolation and elucidation of halogenated and non-halogenated bis-bibenzylys from a species in the Mastigophoroideae (321). The former compound has been obtained from *Plagiochila deflexa* (33), as mentioned earlier. Matrix-assisted laser desorption/ionization time-of flight (MALDI-TOF) mass measurement confirmed that the chlorinated compounds are not artifacts (766).

Guo and associates reported the rapid identification of bis-bibenzylys using electron ionization (EI)-TOF and electrospray ionization triple-quadrupole (ESI-TQ) mass spectrometry (272). Xing and colleagues developed a simple and rapid LC-DAD/MS/MS method using full-scan MS, MS/MS precursor ion scan, and MS/MS product-ion scan modes for the identification of bis-bibenzylys including when present in the crude ether extracts of liverworts (968).

Bazzania trilobata is a rich source of aromatic compounds, such as cyclic bis-bibenzylys and lignans. The ethyl acetate-soluble fraction of the methanol extract of *B. trilobata* was purified by a combination of column chromatography on Sephadex LH-20, followed by HPLC, to afford 11 cyclic bis-bibenzylys named

bazzanins A-K (**1616–1626**) (522). Compounds A-I are isoplagiochin C (**1606**) derivatives with one to six chlorine atoms in their molecules, with compound J (**1625**) being the 16,6'-dichloro derivative of isoplagiochin D (**1607**) (40). Bazzanin A (**1616**) was assigned as 6'-chloroisoplagiochin C by DCI mass spectrometry and from its COSY, HMBC, and NOESY NMR spectroscopic data. Bazzanin B (**1617**) has been shown to possess two chlorine atoms in its molecule. The positions of the chlorine atoms for compound **1617** were based on a comparison of its spectroscopic data with those of **1616** and by detailed analysis of the COSY, HMBC, and NOESY spectra. Proton H-7', when compared with that of **1616**, showed an alteration of multiplicity in the ^1H NMR spectrum from a doublet ($J = 12$ Hz) to a singlet, indicating the position of the second chlorine atom to be C-8'. Bazzanins C-J (**1618–1625**) were assigned with a chlorine atom at C-8' by spectroscopic data comparison with isoplagiochin C and bazzanin A (**1616**). All other structural assignments for these new compounds were supported by analysis of their COSY, HMBC, and NOESY spectra. Bazzanin J (**1625**) is a C-7' and C-8' reduced compound for which the structure was again determined by detailed analysis of its COSY, HMBC, and NOESY spectra. Bazzanin K (**1626**) possesses a bibenzyl and phenanthrene moiety, and its structure also was based on the analysis of 2D-NMR data (522). The enantiomeric purities of bazzanins A-I (**1616–1624**), K (**1626**), and S (**1634**) were determined by means of enantioselective chromatography with online measurement of CD spectra, as mentioned earlier (522, 715).

The ether extract of *Bazzania tricrenata* also produces three chlorinated bis-bibenzyls, of which the structure of one of these was characterized as 10,12,2',10',14'-pentachloro-7',8'-dehydroisopalagiochin D (**1611**) (84).

The methanol extract of the Costa Rican *Lepidozia incurvata* was fractionated on Sephadex LH-20 to afford several isoplagiochin C-type chlorinated bis-bibenzyls, named bazzanins L-R (**1627–1633**). The structures of all of these newly isolated compounds were established using a combination of their CI/MS and DCI/MS and 2D-NMR spectroscopic data, as reported (714). These chlorinated bis-bibenzyls were the first such compounds recorded in a *Lepidozia* species, although the genus *Bazzania*, belonging to the same family Lepidoziaceae, produces a number of chlorinated bis-bibenzyls, bazzanins A-K, along with some non-chlorinated bis-bibenzyls (522).

The presence of atropisomers among the bis-bibenzyls has been discussed by Hashimoto *et al.* (313) and Asakawa *et al.* (75). Bazzanins L-R (**1627–1633**) displayed specific rotations between $[\alpha]_{\text{D}} = +54$ and $+225^\circ \text{ cm}^2 \text{ g}^{-1} 10^{-1}$ (714).

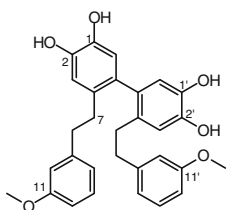
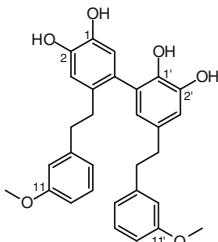
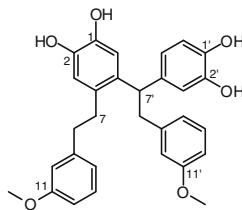
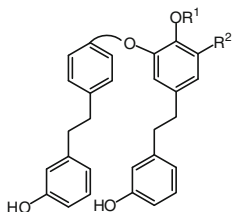
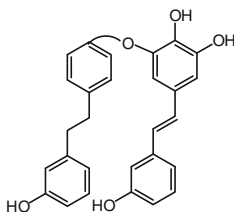
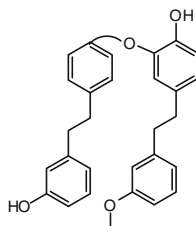
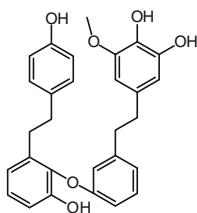
Monoclea forsteri elaborates perrottetin E (**1638**) (0.01% of the total extract) and marchantin-type bis-bibenzyls and fatty acids possessing yne-enone and yne-enol groups (40). Reinvestigation of the ether extract of this same species gave perrottetin E (**1638**) in a good yield (22.2% of the crude extract). However, neither marchantins nor unsaturated fatty acids were identified (Omatsu 2009). The ether extracts of *Jungermannia comata* (583) and *Jungermannia infusca* (584) were purified on Sephadex-20 to yield perrottetin E (**1638**) as a major component (2 g from 8.3 g of the crude extract from the latter species).

Except for the presence of perrottetin E (**1638**) in the Japanese fern, *Hymenophyllum barbatum* (**633**), acyclic bibenzyls have been found only in the Marchantiophyta (**75**), and thus they are the most significant chemical markers in this class. Chlorinated isoplagiochin C- and D-type bis-bibenzyls are known to occur in several genera of the Marchantiophyta, namely, *Herbertus* (**321**), *Mastigophora* (**321**), and *Plagiochila* (**32**).

Speicher and coworkers accomplished the total synthesis of 12-chloroisopalgiochin D (**1612**) isolated from *Plagiochila* species, and 6'-chloroisopalgiochin C (= bazzanin A) (**1616**) and 6,12'-dichloroisoplagiochin D (= bazzanin J) (**1625**) from *Bazzania trilobata*, by construction of the biaryl moiety using regioselective *Suzuki* protocols and coupling to acyclic bibenzyl and cyclic bibenzyls by *Wittig* and *MacMurry* procedures, followed by hydrogenation and deprotection (**767**).

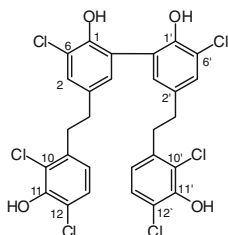
Anton and associates studied a methanol extract of the Costa Rican *Plagiochila deflexa* and isolated four new bis-bibenzyls, named isoplagiochin G (**1610**), plagilin (**1635**), isoplagilin (**1636**), and plagiolin (**1637**), together with the known riccardin C (**1566**), and isoplagiochins C (**1606**), D (**1607**), and F (**1609**) (**34**). Their structures were proved by 2D-NMR spectroscopic methods. The biphenyl linkages at C-5-C-5' in **1635** C-5-C-6' in **1636**, and C-5-C-7' in **1637**, between two molecules of 3,4-dihydroxy-3'-methoxybibenzyl (**1494**), were established by the analysis of NOESY correlations. The NMR spectrum of isoplagiochin G (**1610**) is similar to that of isoplagiochin A (**1604**) indicating that **1610** contains a benzophenone moiety. The position of a phenyl ether linkage at C-13 was confirmed by means of a NOESY experiment. This is the first report of the presence of bibenzyls with a C-C linkage of a phenyl C-atom to a C-atom of the ethano bridge (**34**). Isoplagiochins C and D were isolated initially from *Plagiochila fruticosa* by *Hashimoto* and associates (**313**). Isoplagiochin F (**1609**) has been found in *Plagiochila permista* var. *integerrima* (**33**).

The Ecuadorian *Frullania convoluta* was found to contain four known bis-bibenzyls, perrottetins E-G (**1638–1640**) and 7',8'-dehydroperrottetin F (**1641**). Their spectroscopic data were identical with those previously reported for these bis-bibenzyls (**226**). While the New Zealand *Lunularia cruciata* produced lunularin (**1477**), perrottetin F (**1639**) isolated from the same species when collected in Japan, was not detected (**616**). *Nardia subclavata* and *Pellia epiphylla* elaborated perrottetin E (**1638**) (**40**) and perrottetin E and its 11'-methyl ether (**1642**), respectively (**84**). Both compounds were isolated from *Pellia epiphylla* and *P. endiviifolia* (**40**).

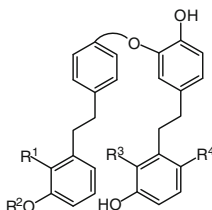
**1635** (plagilin)**1636** (isoplugin)**1637** (plagiolin)**1638** $R^1=R^2=H$ (perrottetin E)**1639** $R^1=H$, $R^2=OH$ (perrottetin F)**1640** $R^1=Me$, $R^2=OH$ (perrottetin G)**1641** (7',8'-dehydroperrrottetin F)**1642** (perrottetin E 11'-methyl ether)**1642a** (paleatin B)

Acyclic bis-biphenyls found in the Marchantiophyta

Jamesoniella colorata was found to contain the new chlorinated bis-biphenyl **1643**. Direct CI mass spectrometry of **1643** indicated the presence of six chlorine atoms in the molecule. The whole structure of this substance was established as 6,6',10,10',12,12'-hexachloroisoperrottetin A by means of its HMBC and NOESY spectra. This was the first isolation of a bis-biphenyl from the genus *Jamesoniella* (340).



1643 (6,6',10,10',12,12'-hexachloro-isoperrottetin A)



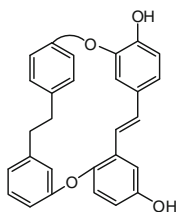
1644 $R^2=Me$, $R^1=R^3=R^4=H$ (perrottetin E-11-methyl ether)

1645 $R^1=R^2=R^3=H$, $R^4=OH$ (14'-hydroxyperrottetin E)

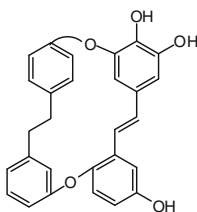
1646 $R^1=R^2=R^4=H$, $R^3=OH$ (10'-hydroxyperrottetin E)

1647 $R^1=R^4=H$, $R^2=Me$, $R^3=OH$ (10'-hydroxyperrottetin E-11-methyl ether)

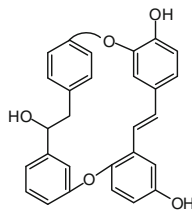
1648 $R^1=R^3=OH$, $R^2=R^4=H$ (10,10'-dihydroxyperrottetin E)



1649 (ptychantol A)



1650 (ptychantol B)



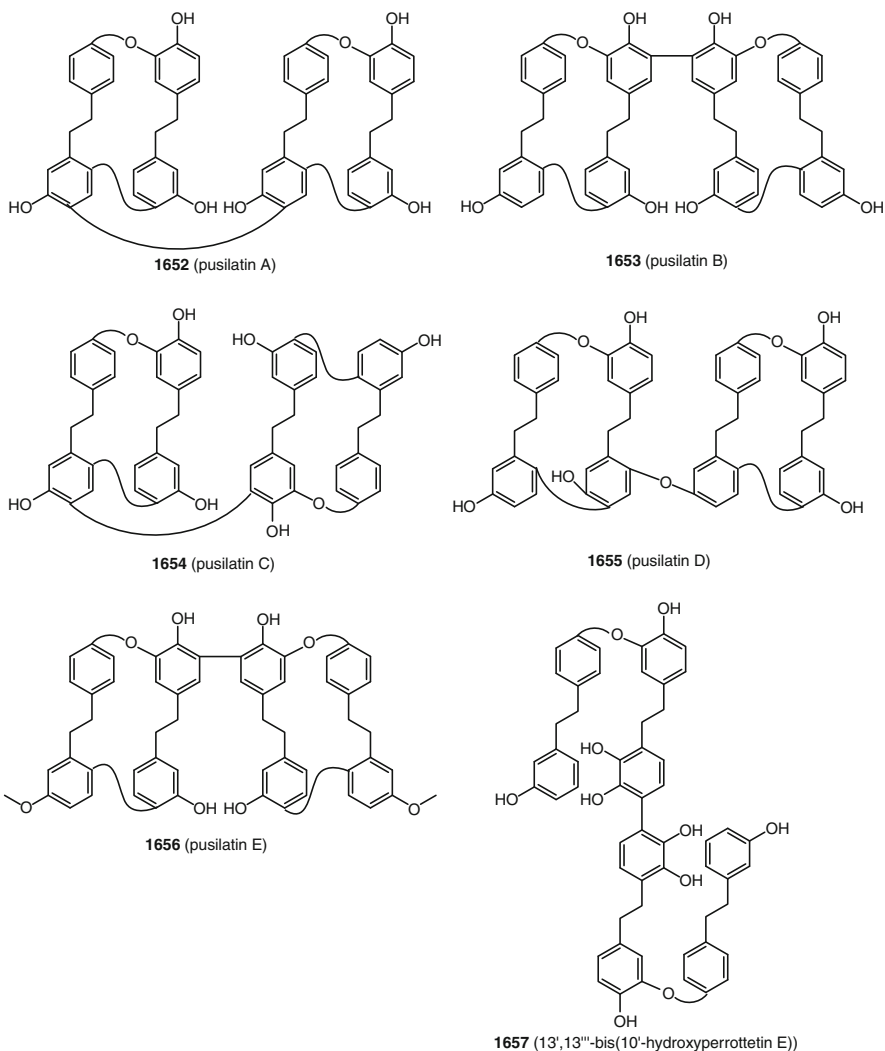
1651 (ptychantol C)

Acyclic bibenzyl-stilbene dimer and cyclic bis-bibenzyis found in the Marchantiophyta

Reinvestigation of the ether extract of the gametophyte of the European *Pellia epiphylla* resulted in the isolation of the five bis-bibenzyis **1644–1648**, and the bis-bibenzyl dimer **1657**, together with the known perrottetin E (**1638**) (175, 182). Compounds **1646** and **1647** were also isolated from the sporophytes of this liverwort (175). Compound **1644** is a methyl ether of perrottetin E according to the molecular formula, with the NMR spectra of **1644** and **1638** showing an overall similarity, except for methoxy group signals in the former compound. The position of the methoxy group at C-11 was confirmed from the NOESY spectrum. Thus, the structure of **1644** was established as perrottetin E 11-methyl ether. Its isomer, perrottetin E 11'-methyl ether (**1642**), has been isolated from *Pellia endiviifolia* (40). Compound **1645** could be assigned as 14'-hydroxyperrottetin E according to the similarity of the NMR spectra of **1645** and 14-hydroxyperrottetin E isolated from *Pellia endiviifolia* (40) and as a result of its total synthesis (729). Previously, compound **1646** was reported as 14'-hydroxyperrottetin E. However, this structure was revised as 10'-hydroxyperrottetin E (**1646**) by the re-evaluation of the NMR spectroscopic data and by independent total synthesis. The Wittig reaction of 4-carbomethoxyphenyl 2'-methoxy-5'-formyl phenyl ether and 2,3-dimethoxybenzyl-phosphonium salt gave a stilbene derivative, followed by catalytic hydrogenation, $LiAlH_4$ hydration, and PCC oxidation to yield 1,2',3'-trimethoxy-4''-formylphenoxybibenzyl, which was further reacted with *m*-methoxybenzylphosphonium salt, followed by hydrogenation and demethylation, to give 10'-hydroxyperrottetin E (**1646**). The structure of **1647** was assigned as 10'-hydroxyperrottetin E 11-methyl ether, according to the similarity of ^1H and ^{13}C

NMR spectra with those of **1646** and by analysis of its NOESY spectrum. Previously, 14,14'-dihydroxyperrottetin E was reported as one of the perrottetin E series from *P. epiphylla*. However, it was revised as 10,10'-dihydroxyperrottetin E (**1648**) by total synthesis, using a twofold *Wittig* reaction, as described above ([182](#)).

The ^1H and ^{13}C NMR spectra of compound **1657**, $\text{C}_{56}\text{H}_{50}\text{O}_{10}$, showed the signals of a bis-bibenzyl, but according to its mass spectrum it resulted from the oxidative combination of two perrottetin units. Analysis of the entire ^1H and ^{13}C NMR data led to the structure 13',13'''-bis(10'-hydroxyperrottetin E) (**1657**) ([182](#)). The proposed structure was confirmed by total synthesis using tetramethoxy-substituted biphenyl-3,3'-dialdehyde as the starting material.



Bis-bibenzyl dimers found in the Marchantiophyta

Three new bis-bibenzyls named ptychantols A-C (**1649**–**1651**), possessing a (*E*)-stilbene moiety, were isolated from the Japanese *Ptychanthus striatus* (Fig. 4.25) (320). The gross structure of ptychantin A was suggested by the analysis of the 2D-NMR data of **1649** and of its permethylated compound. The structure proposed was confirmed by X-ray crystallographic analysis. The structures of compounds **1650** and **1651** were also determined by a combination of their 2D-NMR spectroscopic data and those of their permethylated derivatives. Ptychantol C (**1651**) is an optically active compound with a negative specific rotation $[\alpha]_D = -14.8^\circ \text{ cm}^2 \text{ g}^{-1} 10^{-1}$ and a series of Cotton effects: $\lambda(\Delta\epsilon) = 289(+10.6)$, 270 (-3.0), 253(+21.2), 235(-30.8) nm(mol $^{-1}$ dm ^{3} cm $^{-1}$). The absolute configuration of **1651** remains to be clarified, however. Ptychantols are the first macrocyclic bis-bibenzyls with a (*E*)-stilbene structure found in a species in the Marchantiophyta, although an acyclic bis-bibenzyl, 7',8'-dehydroperrottetin F (**1641**), which has been isolated from *Lunularia cruciata* (40), has a (*E*)-stilbene moiety. Ptychantol B (**1650**) might be formed from **1641** by phenolic oxidation, as shown in Scheme 4.52 (320).

Schistochila glaucescens has been known to produce the cyclic bis-bibenzyls, neomarchantin A (**1595**), neomarchantin B (**1596**), and marchantin C (**1579**) (40). Further fractionation of the dichloromethane extract of the same species resulted in the isolation of two new cyclic bis-bibenzyls, glaucescens bis-bibenzyl (GBB) A (**1658**) and GBB B (**1659**), together with neomarchantins A (**1595**) and B (**1596**) (712). The new bibenzyls were shown to be isomers by electrospray-ionization MS. Both bibenzyls showed very similar NMR spectra with those of neomarchantin B (**1596**), indicating that these compounds possess a neomarchantin B (**1596**) moiety with a sesquiterpenoid unit. Further analysis of the HMBC and NOESY spectra of **1658** and **1659** led to the full structures of these bibenzyls. Scher and colleagues proposed the biosynthesis of both compounds, as shown in Scheme 4.53 (712). From farnesyl pyrophosphate, a furanosesquiterpene might be formed, followed by cyclization with bis-bibenzyl orthoquinones to afford **1658** and **1659**.

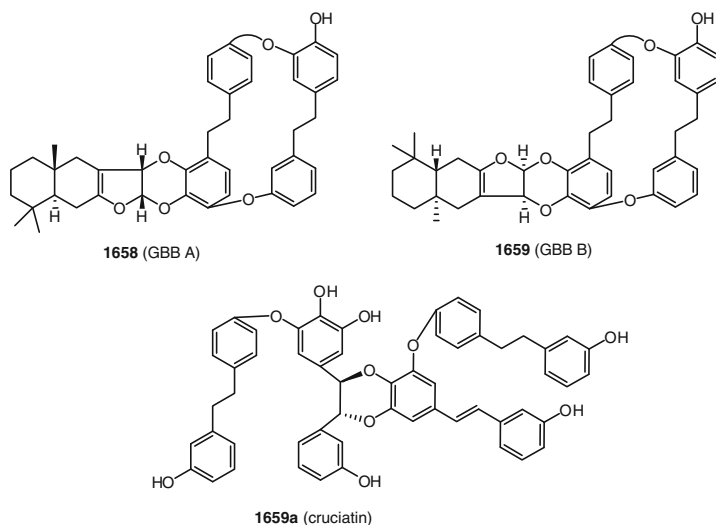




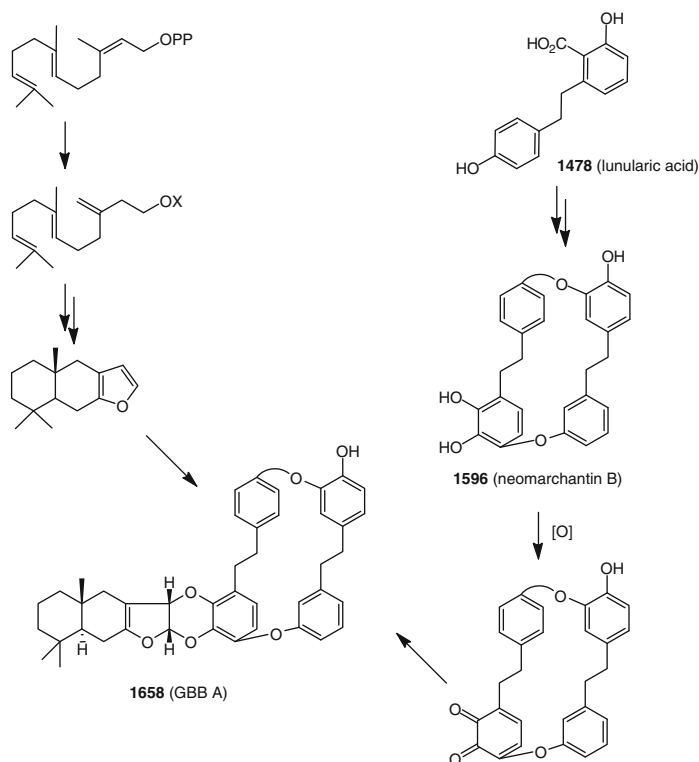
Fig. 4.25 *Ptychanthus striatus*

Reinvestigation of the ether extract of *S. glaucescens* collected in various locations in New Zealand led to the isolation of these same bis-bibenzyl sesquiterpene dimers (**1658** and **1659**), along with marchantin C (**1579**) and neomarchantin A (**1595**) (84, 607).

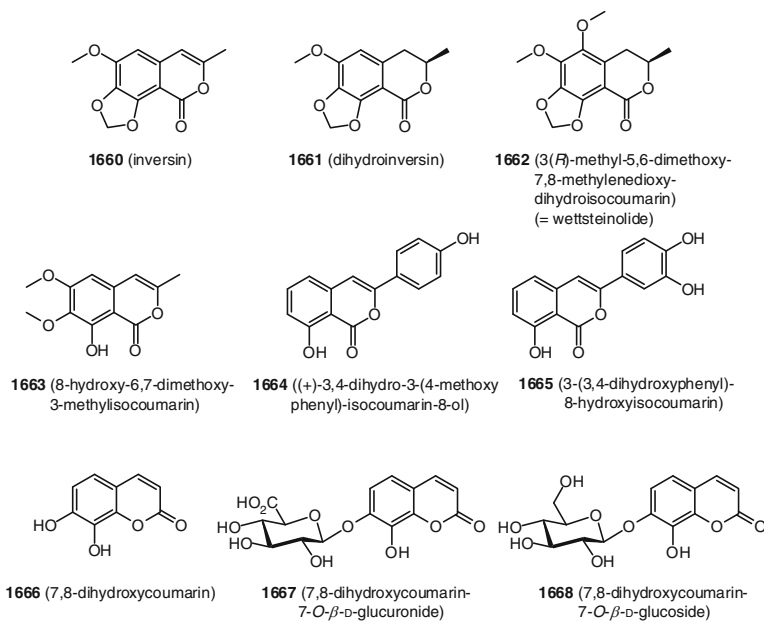
4.5.3 Other Aromatic Compounds

Liverworts produce not only bibenzyls and bis-bibenzyls but also many other simple aromatic compounds, such as benzoates, cinnamates, alkyl phenols, naphthalenes, phthalides, phenanthrenes, isocoumarins and coumarins, chromones, and lignans, among others (Table 4.7).

The Taiwanese *Wettsteinia inversa* produces the two isocoumarin derivatives inversin (**1660**) and dihydroinversin (**1661**), together with 2,4,7-trimethoxynaphthalene (**1682**) (40). However, naphthalene and isocoumarin derivatives with a tetra-substituted benzene ring as isolated from *Wettsteinia schusterana* have not been found in *W. inversa*. Thus, from the standpoint of chemistry it is suggested that *W. schusterana* is a one-step more evolved species than *W. inversa*. The full structural assignment for wettstein C (**1681**) isolated from the Taiwanese *W. inversa* was reported by Kiang and associates (407). The same authors reported that the Taiwanese *W. inversa* elaborates three antiplatelet-active isocoumarin derivatives, inversin (**1660**), dihydroinversin (**1661**), and 8-hydroxy-6,7-dimethoxy-3-methylisocoumarin (**1663**).



Scheme 4.53 Possible biogenesis pathways for the molecule **1658** (GBB A) consisting of a cyclic bis-benzyl and a sesquiterpene ether



The New Zealand *Wettsteinia schusterana* is a rich source of highly oxygenated naphthalene derivatives. The isolation and the gross structures of three naphthalene derivatives, wettsteins A (**1679**), B (**1680**), and C (**1681**), and two isocoumarins, dihydroinversin (**1661**) and wettsteinolide (**1662**), have been reported as unpublished results (40). The detailed ^1H and ^{13}C NMR data and the complete structure determinations of compounds **1681**, **1661**, and **1662** were published by Asakawa *et al.* (69, 70).

Fractionation of the dichloromethane extract of an axenic culture of *Plagiochila adianthoides* resulted in the isolation of the optically active (+)-3,4-dihydro-3-(4-methoxyphenyl)isocoumarin-8-ol (**1664**) (911). Racemic **1664** has been found in the higher plant, *Hydrangea macrophylla* var. *thubergii* (385). This was the first isolation of the (+)-isomer of **1664** from a natural source.

The methanol extract of a sterile culture of *Marchantia polymorpha* was fractionated by column chromatography and HPLC to afford **1665**, for which the structure was deduced as 3-(3,4-dihydroxyphenyl)-8-hydroxyisocoumarin, by analysis of its ^1H and ^{13}C NMR spectra and by comparison of its overall spectroscopic data with published values for lunularic acid and 3-phenylisocoumarin (8). 7,8-Dihydroxycoumarin (**1666**) was isolated from an ethanol extract of the Chinese liverwort, *Lepidozia vitrea* (497). This was the first isolation of a coumarin derivative from the latter species.

7,8-Dihydroxycoumarin-7-*O*- β -D-glucuronide (**1667**) was isolated from *Bazzania trilobata*. The presence of the glucuronic acid unit was confirmed by the ^{13}C NMR spectrum and the entire structure of **1667** was proposed based on an overall 2D-NMR analysis (715). The presence of coumarin derivatives is rare in the liverworts. Daphnin, 7,8-dihydroxy-7-*O*- β -D-glucopyranoside (**1668**), was found in *Bazzania trilobata* (521) and *Lepidozia reptans* (705).

Figueiredo and associates identified 2,5-dimethylstyrene (**1669**) in the essential oils of four European *Plagiochila* species, namely, *P. bifaria*, *P. maderensis*, *P. retrorsa*, and *P. stricta* (221).

Table 4.7 Other aromatic compounds found in the Marchantiophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1660	Inversin	C ₁₂ H ₁₀ O ₅	197-201		<i>Wettsteinia inversa</i>	(407)	
1661	Dihydroinversin [(3 <i>R</i>)-Methyl-6-methoxy-7,8-methylenedioxy-dihydroisocoumarin]	C ₁₂ H ₁₂ O ₅	118-119	-7.0	<i>Wettsteinia schusterana</i> <i>Wettsteinia inversa</i>	(69) (407)	
1662	(3 <i>R</i>)-Methyl-5,6-dimethoxy-7,8-methylenedioxydihydroisocoumarin (=Wettsteininole)	C ₁₃ H ₁₄ O ₆		-13.2	<i>Wettsteinia schusterana</i>	(69)	
1663	8-Hydroxy-6,7-dimethoxy-3-methylisocoumarin (=Reticulol monomethyl ether)	C ₁₂ H ₁₂ O ₅	178-180		<i>Wettsteinia inversa</i>	(407)	
1664	(+)-3,4-Dihydro-3-(4-methoxyphenyl)isocoumarin-8-ol	C ₁₆ H ₁₄ O ₄	105	+90.6	<i>Plagiochila adianthoides</i>	(911)	
1665	3-(3,4-Dihydroxyphenyl)-8-hydroxyisocoumarin	C ₁₅ H ₁₀ O ₅			<i>Marchantia polymorpha</i>	(8)	Cell culture
1666	7,8-Dihydroxycoumarin	C ₉ H ₆ O ₄	250-252		<i>Lepidozia vitrea</i>	(497)	
1667	7,8-Dihydroxycoumarin-7- <i>O</i> -β-D-glucuronide	C ₁₅ H ₁₄ O ₁₀		-75.1	<i>Bazzania trilobata</i>	(715)	
1668	7,8-Dihydroxycoumarin-7- <i>O</i> -β-D-glucoside	C ₁₅ H ₁₆ O ₉			<i>Bazzania trilobata</i> <i>Lepidozia reptans</i> <i>Plagiochila bifaria</i> <i>Plagiochila maderensis</i> <i>Plagiochila retrorsa</i> <i>Plagiochila stricta</i> <i>Radula boryana</i> <i>Asterella</i> (?) <i>Conocephalum conicum</i>	(521) (705) (221) (221) (221) (221) (224) (71) (487)	
1669	2,5-Dimethylstyrene	C ₁₀ H ₁₂					
1670	3,4-Dimethoxystyrene (=3,4-Dimethoxy-1-vinylbenzene)	C ₁₀ H ₁₂ O ₂			<i>Marchesinia brachiata</i>	(543) (880) (594)	

1671	<i>p</i> -Vinylanisole	C ₉ H ₁₀ O ₂		<i>Drepanolejeunea</i> <i>madagascariensis</i>	(247)	
1672	2,4,5-Trimethoxystyrene	C ₁₁ H ₁₄ O ₃	54.57	<i>Marchesinia brachiata</i>	(594)	
1673	Methyleugenol	C ₁₁ H ₁₄ O ₂		<i>Marchesinia mackaii</i>	(220)	
1674	(<i>Z</i>)-Methylisoeugenol	C ₁₁ H ₁₄ O ₂		<i>Marchesinia mackaii</i>	(220)	
1675	(<i>E</i>)-Methylisoeugenol	C ₁₁ H ₁₄ O ₂		<i>Marchesinia mackaii</i>	(220)	
1676	α -Asarone	C ₁₂ H ₁₆ O ₃		<i>Marchesinia mackaii</i>	(220)	
1677	β -Asarone	C ₁₂ H ₁₆ O ₃		<i>Marchesinia mackaii</i>	(220)	
1678	γ -Asarone (=2,4,5- Trimethoxyallylbenzene)	C ₁₂ H ₁₆ O ₃		<i>Marchesinia mackaii</i>	(220)	
1679	Wetstein A	C ₁₃ H ₁₂ O ₄		<i>Plagiochila bifaria</i>	(221)	
1680	Wetstein B	C ₁₃ H ₁₂ O ₄		<i>Adelanthus decipiens</i>	(695)	
1681	Wetstein C (=1,2,3- Trimethoxynaphthalene)	C ₁₃ H ₁₄ O ₃		<i>Wetsteinia schusterana</i>	(70)	
1682	2,4,7-Trimethoxynaphthalene	C ₁₃ H ₁₄ O ₃		<i>Adelanthus decipiens</i>	(695)	
1683	1,2,4-Trimethoxynaphthalene	C ₁₃ H ₁₄ O ₃		<i>Wetsteinia schusterana</i>	(70)	
1684	1,2,3,4-Tetramethoxynaphthalene	C ₁₄ H ₁₆ O ₄		<i>Adelanthus decipiens</i>	(695)	
1685	2,3,6'-Tricarboxy-6,7-dihydroxy-1(3')- 2'-pyranonyl-1,2-dihydronaphthalene (=Jamesopyrone)	C ₁₈ H ₁₂ O ₁₀	+54.9	<i>Wetsteinia inversa</i>	(407)	<i>in vitro</i>
1686	2,3,6'-Tricarboxy-6,7-dihydroxy-1(3')- 2'-pyranonyl-1,2-dihydronaphthalene- 9-methyl ester	C ₁₉ H ₁₄ O ₁₀	+33.5	<i>Wetsteinia schusterana</i>	(69)	Culture
1687	2,3,6'-Tricarboxy-6,7-dihydroxy-1(3')- 2'-pyranonyl-1,2-dihydronaphthalene- 10-methyl ester	C ₁₉ H ₁₄ O ₁₀	+50.5	<i>Wetsteinia inversa</i>	(40)	<i>in vitro</i>
1688	2,6'-Dicarboxy-6,7-dihydroxy-1(3')- 2'-pyranonyl-1,2-dihydronaphthalene (=Scapaniapyrone)	C ₁₇ H ₁₂ O ₈	+135.4	<i>Adelanthus decipiens</i>	(695)	Culture
				<i>Jamesoniella autumnalis</i>	(809)	<i>in vitro</i>
				<i>Jamesoniella autumnalis</i>	(809)	Culture
				<i>Jamesoniella autumnalis</i>	(809)	<i>in vitro</i>
				<i>Jamesoniella autumnalis</i>	(809)	Culture

(continued)

Table 4.7 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{ g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1689	2,3-Dicarboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)naphthalene	$\text{C}_{18}\text{H}_{12}\text{O}_8$			<i>Jamesoniella autumnalis</i>	(809)	<i>in vitro</i> Culture
1690	Epiphylllic acid [2,3-Dicarboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-1,2-dihydronaphthalene]	$\text{C}_{18}\text{H}_{14}\text{O}_8$			<i>Bazzania trilobata</i> <i>Chiloscyphus polyanthus</i> <i>Lepidozia incurvata</i> <i>Lophocolea heterophylla</i>	(523) (183) (183) (823)	<i>in vitro</i> Culture
1691	(-)-9,2''-Epiphylloloyl-L-malic acid	$\text{C}_{22}\text{H}_{18}\text{O}_{12}$		-61.0	<i>Lophocolea heterophylla</i>	(823)	<i>in vitro</i> Culture
1692	Epiphylllic acid-7- <i>O</i> - β -glucoside-10-methyl ester	$\text{C}_{25}\text{H}_{26}\text{O}_{13}$		-124.1	<i>Lepicolea ochroleuca</i>	(177)	<i>in vitro</i> Culture
1693	Epiphylllic acid-7- <i>O</i> - β -glucoside-10,5'''- <i>O</i> -shikimic acid ester	$\text{C}_{31}\text{H}_{32}\text{O}_{17}$		-137.4	<i>Lepicolea ochroleuca</i>	(177)	
1694	Epiphylllic acid-7- <i>O</i> - β -glucoside-9,1'''- <i>O</i> -heptitol ester-10,5'''- <i>O</i> -shikimic acid ester	$\text{C}_{38}\text{H}_{46}\text{O}_{23}$		-119.1	<i>Lepicolea ochroleuca</i>	(177)	
1695	Epiphylllic acid-9,5'''- <i>O</i> -10,5'''- <i>O</i> -bis (shikimic acid ester)	$\text{C}_{32}\text{H}_{30}\text{O}_{16}$		-243.6	<i>Lepicolea ochroleuca</i>	(177)	
1696	Epiphylllic acid-7- <i>O</i> - β -glucoside-9,6''- <i>O</i> -shikimic acid ester-10,4'''- <i>O</i> -(5'''',9'''', <i>O</i> -caffeic acid ester)-trilobatinic acid ester	$\text{C}_{48}\text{H}_{48}\text{O}_{26}$		-0.703	<i>Lepidozia vitrea</i>	(497)	
1697	3-Carboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-naphthalene	$\text{C}_{17}\text{H}_{12}\text{O}_6$			<i>Bazzania trilobata</i> <i>Chiloscyphus polyanthus</i> <i>Jungermannia exsertifolia</i> subsp. <i>cordifolia</i> <i>Lepidozia incurvata</i> <i>Pallavicinia subclinata</i>	(523) (183) (183) (183) (183) (882)	

1698	5,5'-bis-[2,3-Dicarboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-1,2-dihydro-naphthalene]	C ₃₆ H ₂₈ O ₁₆	-106.1	<i>Bazzania trilobata</i>	(523)
1699	Trilobatin A	C ₂₇ H ₃₆ O ₁₄	-85.3	<i>Bazzania trilobata</i>	(523)
1700	Trilobatin A-1''-methyl ester	C ₂₇ H ₃₈ O ₁₄	-75.3	<i>Bazzania trilobata</i>	(523)
1701	Trilobatin B	C ₂₆ H ₃₈ O ₁₃	-35.9	<i>Bazzania trilobata</i>	(523)
1702	Trilobatin C	C ₂₇ H ₃₆ O ₁₂	-80.1	<i>Bazzania trilobata</i>	(523)
1703	Trilobatin D	C ₂₅ H ₃₂ O ₁₃	-146.7	<i>Bazzania trilobata</i>	(713)
1704	Trilobatin E	C ₄₃ H ₃₆ O ₂₁		<i>Bazzania trilobata</i>	(713)
1705	Trilobatin F	C ₄₃ H ₃₄ O ₂₂	-75.3	<i>Bazzania trilobata</i>	(713)
1706	Trilobatin G	C ₄₃ H ₃₄ O ₂₂	-20.0	<i>Bazzania trilobata</i>	(713)
1707	Trilobatin H	C ₄₂ H ₄₂ O ₂₃	-164.6	<i>Bazzania trilobata</i>	(713)
1708	Trilobatin I	C ₄₃ H ₄₂ O ₂₃	-84.0	<i>Bazzania trilobata</i>	(713)
1709	Trilobatin J	C ₃₂ H ₄₆ O ₂₆	-164.6	<i>Bazzania trilobata</i>	(713)
1710	Trilobatin K	C ₃₃ H ₃₈ O ₁₇	-12.3	<i>Bazzania trilobata</i>	(713)
1711	Bazzania acid	C ₁₈ H ₁₆ O ₁₁	-16.5	<i>Bazzania trilobata</i>	(523)
1712	3-Carboxy-6-methoxy-1-(3',4'-dihydroxyphenyl)-naphthalene-7-O- α -L-rhamnopyranoside	C ₃₄ H ₂₄ O ₁₀	-72.0	<i>Lepidozia incurvata</i>	(183)
1713	3-Carboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-naphthalene-9,2''-O-malic acid ester	C ₂₁ H ₁₆ O ₁₀	-7.5	<i>Chiloscyphus polyanthos</i>	(183)
1714	3-Carboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-naphthalene-9,5''-O-shikimic acid ester	C ₂₃ H ₂₀ O ₁₀	-14.0	<i>Jungmannia exsertifolia</i> subsp. <i>cordifolia</i>	(183)
1715	Erimopyrone	C ₁₈ H ₁₂ O ₁₀	-69.8	<i>Moerckia erimona</i>	(820)
1716	Erimopyrone 9-methyl ester	C ₁₉ H ₁₄ O ₁₀	-68.8	<i>Moerckia erimona</i>	(820)
1717	Pelliatin	C ₃₃ H ₂₈ O ₁₇	-106.7	<i>Pellia epiphylla</i>	(181)
1718	2-Hydroxy-3,4,5,6-tetramethoxyacetophenone	C ₁₂ H ₁₆ O ₆		<i>Adelanthus decipiens</i>	(695)
1719	2,3,4,6-Tetramethoxyacetophenone	C ₁₂ H ₁₆ O ₅		<i>Adelanthus decipiens</i>	(695)

(continued)

Table 4.7 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{ g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1720	2-Hydroxy-3,4,6-trimethoxy-acetophenone	$\text{C}_{11}\text{H}_{14}\text{O}_5$			<i>Adelanthus decipiens</i> <i>Plagiochila fasciculata</i>	(695) (72) (481) (607)	
1721	2-Hydroxy-4,6-dimethoxy-acetophenone	$\text{C}_{10}\text{H}_{12}\text{O}_4$			<i>Prilidium pulcherrimum</i> <i>Adelanthus decipiens</i> <i>Plagiochila fasciculata</i>	(271) (695) (72) (481)	
1722	2,4-Dihydroxy-6-methoxyacetophenone	$\text{C}_9\text{H}_{10}\text{O}_4$			<i>Heteroscypus</i> sp.	(607)	
1723	2,3,4,5,6-Pentamethoxyacetophenone	$\text{C}_{13}\text{H}_{18}\text{O}_6$			<i>Adelanthus decipiens</i>	(635)	
1724	2,4,6-Trihydroxyacetophenone-3,5-di-C-glucoside	$\text{C}_{30}\text{H}_{38}\text{O}_{14}$			<i>Adelanthus lindenbergianus</i>	(695) (116)	
1725	2,4,6-Trihydroxyacetophenone-2-O-(2'),3-C-(1'')-desoxy- β -D-fructofuranoside-5-C- α -D-glucopyranoside	$\text{C}_{30}\text{H}_{36}\text{O}_{13}$			<i>Lepicolea ochroleuca</i> <i>Adelanthus lindenbergianus</i>	(177) (116)	
1726	Isovanillin	$\text{C}_8\text{H}_8\text{O}_3$			<i>Prilidium pulcherrimum</i>	(271)	
1727	Methyl salicylate	$\text{C}_8\text{H}_8\text{O}_3$			<i>Chandonanthus hirtellus</i>	(494)	
1728	Methyl 2,4-dihydroxybenzoate	$\text{C}_8\text{H}_8\text{O}_4$			<i>Prilidium pulcherrimum</i>	(271)	
1729	Orsellinic acid methyl ester	$\text{C}_9\text{H}_{10}\text{O}_4$			<i>Blasia pusilla</i> <i>Frullania falciloba</i> <i>Frullania fugax</i>	(971) (78) (78)	
1730	Orsellinic acid ethyl ester	$\text{C}_{10}\text{H}_{12}\text{O}_4$			<i>Frullania probosciphora</i> <i>Prilidium pulcherrimum</i> <i>Prilidium pulcherrimum</i>	(78) (271) (271)	

1731	Pulcherriminin	$C_{21}H_{23}O_8$	<i>Prilidium pulcherrimum</i>	(271)
1732	Methyl 3-methoxyorsellinate	$C_{10}H_{12}O_5$	<i>Frullania squarrosula</i>	(84)
1733	Methyl 3-hydroxyorsellinate	$C_9H_{10}O_5$	<i>Frullania squarrosula</i>	(84)
1734	Demethyl everminic acid (=Orsellinic acid)	$C_8H_8O_4$	<i>Frullania squarrosula</i>	(84)
1735	Everminic acid	$C_9H_{10}O_4$	<i>Frullania squarrosula</i>	(971)
1736	Everminic acid methyl ester	$C_{10}H_{12}O_4$	<i>Blasia pusilla</i>	(221)
			<i>Plagiochila bifaria</i>	(277)
				(333)
			<i>Plagiochila killarniensis</i>	(696)
			<i>Plagiochila maderensis</i>	(221)
			<i>Plagiochila retrorsa</i>	(221)
			<i>Plagiochila stricta</i>	(221)
1737	Methyl 4,6-dimethyl-2-methylbenzoate	$C_{11}H_{14}O_4$	<i>Plagiochila killarniensis</i>	(696)
1738	Atracic acid	$C_{10}H_{12}O_4$	<i>Frullania brasiliensis</i>	(98)
1739	Methyl 6-methoxy-2-methyl-3,4-methylenedioxybenzoate	$C_{11}H_{12}O_5$	<i>Plagiochila bifaria</i>	(221)
				(333)
			<i>Plagiochila killarniensis</i>	(696)
			<i>Plagiochila maderensis</i>	(221)
			<i>Plagiochila retrorsa</i>	(221)
			<i>Plagiochila spinulosa</i>	(165)
				(617)
1740	Methyl 6-hydroxy-2-methyl-3,4-methylenedioxybenzoate	$C_{10}H_{10}O_5$	<i>Plagiochila stricta</i>	(221)
			<i>Plagiochila bifaria</i>	(221)
				(333)
			<i>Plagiochila killarniensis</i>	(696)
			<i>Plagiochila maderensis</i>	(221)
			<i>Plagiochila retrorsa</i>	(221)
			<i>Plagiochila stricta</i>	(221)
1741	Methyl 3,4,6-trimethoxy-2-methyl-benzoate	$C_{12}H_{16}O_5$	<i>Plagiochila spinulosa</i>	(165)
			<i>Plagiochila killarniensis</i>	(696)

(continued)

Table 4.7 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ °cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1742	Methyl 2,3,5-trimethoxy-6-methyl-benzoate	C ₁₁ H ₁₆ O ₅			<i>Plagiochila spinulosa</i>	(617)	
1743	Methyl 2,6-dihydroxy-4-methoxy-3-(3-methyl-2-butenyl)benzoate	C ₁₄ H ₁₈ O ₅	72-73		<i>Pedinophyllum interruptum</i>	(214)	
1744	Methyl 2,4,6-trihydroxy-3-(3-methyl-2-butenyl)benzoate	C ₁₃ H ₁₆ O ₅			<i>Pedinophyllum interruptum</i>	(214)	
1745	Methyl 2,4,6-trihydroxy-3-(2-hydroperoxy-3-methyl-3-butenyl)benzoate	C ₁₃ H ₁₆ O ₇			<i>Pedinophyllum interruptum</i>	(214)	
1746	Vanillic acid methyl ester (methyl 4-hydroxy-3-methoxybenzoate)	C ₉ H ₁₀ O ₄			<i>Trichocolea pluma</i>	(490) (494)	
1747	Trichocolein	C ₁₄ H ₁₂ O ₄			<i>Trichocolea lanata</i> <i>Trichocolea pluma</i>	(72) (490)	
1748	Tomentellin	C ₁₉ H ₂₄ O ₅			<i>Trichocolea hatcheri</i> <i>Trichocolea mollissima</i>	(91) (72) (653)	
1749	(E)-Isotomentellin	C ₁₉ H ₂₄ O ₅			<i>Trichocolea pluma</i>	(490) (494)	
1750	(Z)-Isotomentellin	C ₁₉ H ₂₄ O ₅			<i>Trichocolea tomentella</i> <i>Trichocolea mollissima</i> <i>Trichocolea pluma</i>	(653) (653) (490) (494)	
1751	Deoxytomentellin	C ₁₉ H ₂₆ O ₄	41-42		<i>Trichocolea hatcheri</i> <i>Trichocolea mollissima</i> <i>Trichocolea tomentella</i>	(91) (653) (653) (494)	
1752	Demethoxytomentellin	C ₁₈ H ₂₂ O ₅			<i>Trichocolea tomentella</i> <i>Trichocolea tomentella</i>	(653) (653)	

1753	Isohydroperoxytomentellin	C ₁₈ H ₂₂ O ₅		<i>Trichocolea tomentella</i>	(99)	
1754	Methyl 4-[(2 <i>E</i>)-3,7-dimethyl-2,6-octadienyl]oxy-3-hydroxybenzoate	C ₁₈ H ₂₄ O ₄		<i>Trichocolea hatcheri</i>	(91)	
1755	Methyl 4-[(3 <i>E</i>)-3,7-dimethyl-5-oxo-3,6-octadienyl]oxy-3-hydroxybenzoate	C ₁₈ H ₂₂ O ₅		<i>Trichocolea hatcheri</i>	(91)	
1756	Methyl 4-[(3 <i>E</i>)-3,7-dimethyl-5-oxo-3-octenyl]oxy-3-hydroxybenzoate	C ₁₈ H ₂₄ O ₅		<i>Trichocolea hatcheri</i>	(91)	
1757	Methyl 4-[(3 <i>E</i>)-3,7-dimethyl-5-oxo-3-octyl]oxy-3-hydroxybenzoate	C ₁₈ H ₂₆ O ₅	– 11.4	<i>Trichocolea hatcheri</i>	(91)	
1758	Methyl 4-[(3 <i>Z</i>)-3,7-dimethyl-5-oxo-3-octenyl]oxy-3-hydroxybenzoate	C ₁₈ H ₂₄ O ₅		<i>Trichocolea hatcheri</i>	(91)	
1759	2,3,7-Trihydroxyphenanthrene	C ₁₄ H ₁₀ O ₃		<i>Marchantia paleacea</i> var. <i>diptera</i>	(436)	
1760	2,3-Dimethoxy-7-hydroxyphenanthrene	C ₁₆ H ₁₄ O ₃		<i>Marchantia polymorpha</i>	(8)	<i>in vitro</i> Culture
1761	2,7-Dihydroxy-3-methoxyphenanthrene	C ₁₅ H ₁₂ O ₃		<i>Marchantia polymorpha</i>	(8)	<i>in vitro</i> Culture
1762	2-Hydroxy-3,5-dimethoxyphenanthrene	C ₁₆ H ₁₄ O ₃		<i>Plagiochila permista</i> var. <i>integerrima</i>	(33)	
1763	2-Hydroxy-3,7-dimethoxyphenanthrene	C ₁₆ H ₁₄ O ₃		<i>Marchantia paleacea</i> var. <i>diptera</i>	(436)	
1764	3-Hydroxy-2,5-dimethoxyphenanthrene	C ₁₆ H ₁₄ O ₃		<i>Marchantia emarginata</i> subsp. <i>tosana</i>	(436)	
1765	3-Hydroxy-2,7-dimethoxyphenanthrene	C ₁₆ H ₁₄ O ₃		<i>Marchantia paleacea</i>	(424)	
1766	3,3'-Dimethoxy-2,2',7,7'-tetrahydroxy-1,1'-biphenanthrene	C ₃₀ H ₂₂ O ₆		<i>Marchantia paleacea</i> var. <i>diptera</i>	(436)	
1767	3-Methoxy-2,2',3,7,7'-penta-hydroxy-1,1'-biphenanthrene	C ₂₉ H ₂₀ O ₆		<i>Marchantia tosana</i>	(459)	<i>in vitro</i> Culture
				<i>Marchantia polymorpha</i>	(8)	<i>in vitro</i> Culture
				<i>Marchantia polymorpha</i>	(8)	Culture

(continued)

Table 4.7 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1768	2,2',3,3',7,7'-Hexahydroxy-1,1'-biphenanthrene	$\text{C}_{28}\text{H}_{18}\text{O}_6$			<i>Marchantia polymorpha</i>	(8)	<i>in vitro</i> Culture
1769	5-Hydroxy-3,4-dimethoxy-9,10-dihydrophenanthrene	$\text{C}_{16}\text{H}_{16}\text{O}_3$	74-76		<i>Riccardia multifida</i>	(583)	
1770	2-Hydroxy-3,5-dimethoxy-9,10-dihydrophenanthrene	$\text{C}_{16}\text{H}_{16}\text{O}_3$			<i>Marchantia paleacea</i>	(424)	
					<i>Plagiochila bifaria</i>	(277)	
						(333)	
					<i>Plagiochila killamensis</i>	(696)	
					<i>Plagiochila permista</i> var. <i>integerrima</i>	(33)	
1771	5-Hydroxy-2,3-dimethoxy-9,10-dihydrophenanthrene	$\text{C}_{16}\text{H}_{16}\text{O}_3$			<i>Plagiochila retrorsa</i>	(698)	
1772	2,3,5-Trimethoxy-9,10-dihydrophenanthrene	$\text{C}_{17}\text{H}_{18}\text{O}_3$			<i>Plagiochila stricta</i>	(699)	
					<i>Plagiochila permista</i> var. <i>integerrima</i>	(33)	
					<i>Plagiochila bifaria</i>	(333)	
					<i>Plagiochila permista</i> var. <i>integerrima</i>	(33)	
1773	2-Hydroxy-3,7-dimethoxy-9,10-dihydrophenanthrene	$\text{C}_{16}\text{H}_{16}\text{O}_3$			<i>Plagiochila retrorsa</i>	(698)	
					<i>Plagiochila stricta</i>	(699)	
					Unidentified <i>Frullania</i> sp.	(426)	
					<i>Plagiochila bifaria</i>	(333)	
					<i>Plagiochila spinulosa</i>	(165)	
					<i>Plagiochila permista</i> var. <i>integerrima</i>	(33)	
1774	2,3,7-Trimethoxy-9,10-dihydrophenanthrene	$\text{C}_{17}\text{H}_{18}\text{O}_3$			<i>Plagiochila retrorsa</i>	(698)	
					<i>Plagiochila stricta</i>	(699)	
					<i>Plagiochila bifaria</i>	(333)	
					<i>Plagiochila spinulosa</i>	(165)	
					<i>Plagiochila permista</i> var. <i>integerrima</i>	(33)	
1775	5-Hydroxy-2,6-dimethoxy-9,10-dihydrophenanthrene	$\text{C}_{16}\text{H}_{16}\text{O}_3$			<i>Plagiochila retrorsa</i>	(698)	
					<i>Plagiochila spinulosa</i>	(165)	
					<i>Plagiochila permista</i> var. <i>integerrima</i>	(33)	

1776	4,5-Dihydroxy-3-methoxy-9,10-dihydrophenanthrene	$C_{15}H_{14}O_3$	<i>Plagiochila bifaria</i> (277) (333) (696) <i>Plagiochila killamienensis</i> (696) <i>Plagiochila permista</i> var. <i>integerrima</i> (33) <i>Plagiochila retrorsa</i> (698) (333) <i>Plagiochila bifaria</i> (699) <i>Plagiochila stricta</i> (698) <i>Plagiochila retrorsa</i> (33) <i>Plagiochila permista</i> var. <i>integerrima</i> (698) <i>Plagiochila retrorsa</i> (165) (617) <i>Plagiochila spinulosa</i> (165) <i>Plagiochila spinulosa</i> (165) <i>Plagiochila spinulosa</i> (617) (165) (165) <i>Plagiochila spinulosa</i> (165) (617) <i>Conocephalum conicum</i> (874) <i>Marchantia polymorpha</i> (667) <i>Marchantia polymorpha</i> (667) <i>Marchantia polymorpha</i> (667)
1777	4-Hydroxy-3,7-dimethoxy-9,10-dihydrophenanthrene	$C_{16}H_{16}O_3$	
1778	3,5-Dihydroxy-4-methoxy-9,10-dihydrophenanthrene	$C_{15}H_{14}O_3$	
1779	2,3,5,7-Tetramethoxy-9,10-dihydrophenanthrene	$C_{18}H_{20}O_3$	
1780	2,5,6-Trimethoxy-9,10-dihydrophenanthrene	$C_{17}H_{18}O_3$	74-76
1781	2,5-Dihydroxy-6-methoxy-9,10-dihydrophenanthrene	$C_{15}H_{14}O_3$	
1782	2-Hydroxy-5,6-dimethoxy-9,10-dihydrophenanthrene	$C_{16}H_{16}O_3$	
1783	2,3,4,7-Tetramethoxy-9,10-dihydrophenanthrene	$C_{18}H_{20}O_4$	134-138
1784	2,3,7-Trihydroxy-4-methoxy-9,10-dihydrophenanthrene	$C_{15}H_{14}O_3$	
1785	2-Hydroxy-3,4,7-trimethoxy-9,10-dihydrophenanthrene	$C_{17}H_{18}O_4$	139-142
1786	2-(3,4-Dihydroxyphenyl)-ethyl- β -D-allopyranoside	$C_{14}H_{20}O_8$	
1787	2-(3,4-Dihydroxyphenyl)-ethyl- β -D-glucopyranoside	$C_{14}H_{20}O_8$	
1788	2-(3,4-Dihydroxyphenyl)-ethyl- <i>O</i> - α -L-rhamnopyranosyl-(1 $\rightarrow$ 2)- β -D-allopyranoside	$C_{20}H_{30}O_{12}$	-76

(continued)

Table 4.7 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1789	2-(3,4-Dihydroxyphenyl)-ethyl- <i>O</i> - β -D-xylopyranosyl-(1 $\rightarrow$ 6)- <i>O</i> - β -D-allopyranoside	C ₁₉ H ₂₈ O ₁₂		-70	<i>Marchantia polymorpha</i>	(667)	
1790	3-Methoxy-4- <i>O</i> - β -D-glucopyranosyl-benzyl alcohol	C ₁₄ H ₂₀ O ₈	92-94	-27.4	<i>Heteroscyphus coalitus</i>	(617)	
1791	4- <i>O</i> -[α -rhamnopyranosyl-(1 $\rightarrow$ 6)- β -D-glucopyranosyl]-3-hydroxybenzyl alcohol	C ₁₉ H ₂₈ O ₁₂		-43.2	<i>Heteroscyphus coalitus</i>	(617)	
1792	3,5-Dimethoxy-4- <i>O</i> - β -D-glucopyranosyl-benzyl alcohol	C ₁₅ H ₂₂ O ₉		-18.0	<i>Plagiochila spinulosa</i>	(617)	
1793	3-Methoxy-4- <i>O</i> -[α -rhamnopyranosyl (1 $\rightarrow$ 2)- β -D-glucopyranosyl] benzyl alcohol	C ₂₀ H ₃₀ O ₁₂		-29.8	<i>Plagiochila spinulosa</i>	(617)	
1794	3,5-Dimethoxy-4-hydroxybenzyl- <i>O</i> - β -D-glucopyranoside	C ₁₅ H ₂₂ O ₉			<i>Plagiochila fruticosa</i>	(617)	
1795	4- <i>O</i> -[α -apiofuranosyl(1 $\rightarrow$ 6)- β -D-glucopyranosyl] styrene	C ₁₉ H ₂₈ O ₁₀		-61.3	<i>Plagiochila fruticosa</i>	(617)	
1796	1-Ethyl-4-hydroxybenzene (=4-Ethylphenol)	C ₈ H ₁₀ O			<i>Leptolejeunea elliptica</i>	(879)	
1797	1-Ethyl-4-methoxybenzene (4-ethylanisole)	C ₉ H ₁₂ O			<i>Leptolejeunea elliptica</i>	(879)	
1798	1-Ethyl-4-acetoxymethoxybenzene	C ₁₀ H ₁₂ O ₂			<i>Leptolejeunea elliptica</i>	(879)	
1799	5-Ethyl-1-methoxy-2,3-methylenedioxybenzene	C ₁₀ H ₁₂ O ₃			<i>Plagiochila rutilans</i>	(693)	
1800	5-Ethyl-1,2,3-trimethoxybenzene	C ₁₁ H ₁₆ O ₃			<i>Plagiochila rutilans</i>	(693)	
1801	1-Methoxy-4-(2-methylpropenyl) benzene	C ₁₁ H ₁₄ O			<i>Radula perrottetii</i>	(826)	
1802	2-Methoxy-6-(3-methyl-2-butenyl)-hydroquinone	C ₁₂ H ₁₆ O ₃			<i>Plagiochila rutilans</i>	(693)	
1803	2-Methoxy-6-(3-methyl-2-butenyl)-1,4-benzoquinone	C ₁₂ H ₁₄ O ₃			<i>Plagiochila rutilans</i>	(693)	

1804	2-Methoxy-4- <i>O</i> -methyl-6-(3-methyl-2-butenyl)-hydroquinone	C ₁₃ H ₁₈ O ₃	<i>Plagiochila rutilans</i>	(693)
1805	2-Methoxy-1- <i>O</i> -methyl-6-(3-methyl-2-butenyl)-hydroquinone	C ₁₃ H ₁₈ O ₃	<i>Plagiochila rutilans</i>	(693)
1806	Killarniensolide (=3-(2'-Hydroxy-4',5'-dimethoxy-benzyl)-7-methoxyphthalide)	C ₁₈ H ₁₈ O ₆	<i>Plagiochila bifaria</i>	(333)
1807	3 α -(4'-Methoxybenzyl)-5,7-dimethoxyphthalide	C ₁₈ H ₁₈ O ₅	<i>Plagiochila killarniensis</i>	(696)
			<i>Frullania falciloba</i>	(78)
			<i>Monoselenium tenerum</i>	(492)
			Unidentified <i>Frullania</i> sp.	(426)
1808	Balanitolide (=3-(3',4'-Dimethoxybenzyl)-7-hydroxy-5-methoxyphthalide)	C ₁₈ H ₁₈ O ₆	<i>Frullania muscicola</i>	(443)
1809	3-(3',4'-Dimethoxybenzyl)-5,7-dimethoxyphthalide	C ₁₉ H ₂₀ O ₆	<i>Frullania muscicola</i>	(443)
1810	3-(4'-Hydroxy-3'-methoxybenzyl)-5,7-dimethoxyphthalide	C ₁₈ H ₁₈ O ₆	<i>Frullania muscicola</i>	(443)
1811	3-(4'-Methoxybenzyl)-7-hydroxy-phthalide	C ₁₆ H ₁₄ O ₄	<i>Plagiochila buchianiana</i>	(330)
1812	3-(4'-Methoxybenzyl)-7-methoxy-phthalide	C ₁₇ H ₁₆ O ₄	<i>Plagiochila diversifolia</i>	(330)
			<i>Plagiochila buchianiana</i>	(330)
			<i>Plagiochila diversifolia</i>	(330)
			<i>Plagiochila longispina</i>	(330)
			<i>Plagiochila diversifolia</i>	(330)
1813	3-(3',4'-Dimethoxybenzyl)-7-methoxyphthalide	C ₁₈ H ₁₈ O ₅	<i>Plagiochila diversifolia</i>	(330)
1814	3-(3',4',5'-Trimethoxybenzyl)-7-methoxyphthalide	C ₁₉ H ₂₀ O ₆	Unidentified <i>Frullania</i> sp.	(426)
1814a	(-)-3 α -(3'-Methoxy-4',5'-methylenedioxy)-5,7-dimethoxyphthalide			

(continued)

Table 4.7 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1815	Corsifuran A	C ₁₆ H ₁₆ O ₃			<i>Corsinia coriandrina</i>	(79)	
1816	Corsifuran B	C ₁₅ H ₁₄ O ₃			<i>Corsinia coriandrina</i>	(920)	
1817	Corsifuran C	C ₁₆ H ₁₄ O ₃			<i>Corsinia coriandrina</i>	(79)	
1818	6-Hydroxy-5-methoxy-2,2-dimethyl-7-(3-methyl-2-butenyl)-chroman	C ₁₇ H ₂₄ O ₃			<i>Corsinia coriandrina</i>	(920)	
					<i>Cephalozia otariensis</i>	(894)	
1819	8-Hydroxy-5-methoxy-2,2-dimethyl-7-(3-methyl-2-butenyl)-chroman	C ₁₇ H ₂₄ O ₃			<i>Metacalypogeia cordifolia</i>	(894)	
1820	2,2-dimethyl-7-(3-methyl-2-butenyl)-chroman-5,8-quinone	C ₁₆ H ₂₀ O ₃			<i>Metacalypogeia cordifolia</i>	(894)	
1821	5-Hydroxy-2,2,2',2'-tetramethyldichroman	C ₁₆ H ₂₂ O ₃	181–185		<i>Metacalypogeia cordifolia</i>	(894)	
1822	2,2,2',2'-Tetramethyldichroman-5-methyl ether	C ₁₇ H ₂₄ O ₃			<i>Metacalypogeia cordifolia</i>	(894)	
1823	Metacalypogin	C ₁₇ H ₂₂ O ₃			<i>Metacalypogeia alternifolia</i>	(748)	
					<i>Metacalypogeia cordifolia</i>	(748)	
1824	Methyl 5,7-dihydroxy-2,2-dimethyl-2 <i>H</i> -chromene-6-carboxylate	C ₁₃ H ₁₄ O ₅			<i>Adelanthus lindenbergianus</i>	(214)	
					<i>Pedinophyllum interruptum</i>	(214)	
1825	Methyl 7-hydroxy-5-methoxy-2,2-dimethyl-2 <i>H</i> -chromene-8-carboxylate	C ₁₄ H ₁₆ O ₅			<i>Adelanthus lindenbergianus</i>	(214)	
					<i>Pedinophyllum interruptum</i>	(214)	
1826	Methyl 8-hydroxy-2,2-dimethyl-2 <i>H</i> -chromene-6-carboxylate	C ₁₃ H ₁₄ O ₄			<i>Pedinophyllum interruptum</i>	(214)	

1827	Methyl 8-methoxy-2,2-dimethyl- 2 <i>H</i> -chromene-6-carboxylate	C ₁₄ H ₁₆ O ₄	<i>Pedinophyllum interruptum</i> (214)
1828	Phenethyl alcohol	C ₈ H ₁₀ O	<i>Isotachis aubertii</i> (288)
1829	Benzyl benzoate	C ₁₄ H ₁₂ O ₂	<i>Isotachis layllii</i> (73) (616) (73)
			Unidentified <i>Isotachis</i> sp. I (616)
			Unidentified <i>Isotachis</i> sp. II (616)
1830	β-Phenethyl benzoate (=2-Phenylethyl benzoate)	C ₁₅ H ₁₄ O ₂	<i>Isotachis aubertii</i> (288) <i>Isotachis montana</i> (73) Unidentified <i>Isotachis</i> sp. II (73)
1831	β-Phenethyl 4-hydroxy- 3-methoxybenzoate	C ₁₆ H ₁₆ O ₄	<i>Balantiopsis cancellata</i> (457) <i>Isotachis montana</i> (616)
1832	(<i>R</i>)-2-Hydroxy-2-phenylethyl benzoate	C ₁₅ H ₁₄ O ₃	<i>Balantiopsis cancellata</i> (457)
1833	Benzyl (<i>E</i>)-cinnamate	C ₁₆ H ₁₄ O ₂	Unidentified <i>Isotachis</i> sp. I (73)
1834	β-Phenethyl (<i>Z</i>)-cinnamate (=2-Phenylethyl (<i>Z</i>)-cinnamate)	C ₁₆ H ₁₆ O ₂	<i>Balantiopsis cancellata</i> (457) <i>Isotachis aubertii</i> (288) <i>Isotachis layllii</i> (73)
1835	β-Phenethyl (<i>E</i>)-cinnamate (=2-Phenylethyl (<i>E</i>)-cinnamate)	C ₁₆ H ₁₆ O ₂	<i>Balantiopsis cancellata</i> (457) <i>Isotachis aubertii</i> (288) <i>Isotachis layllii</i> (73) Unidentified <i>Isotachis</i> sp. I (73)
1836	(<i>E</i>)-Methyl cinnamate	C ₁₀ H ₁₀ O ₂	<i>Conocephalum conicum</i> (880) (945)
1837	1-Octen-3(<i>R</i>)-yl cinnamate	C ₁₇ H ₂₀ O ₂	<i>Isotachis layllii</i> (84)

(continued)

Table 4.7 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1838	Atranorin	C ₁₉ H ₁₈ O ₈			<i>Trocholejeunea sandvicensis</i>	(460)	
1839	Methyl lecanorate	C ₁₇ H ₁₆ O ₇			Unidentified <i>Frullania</i> sp.	(426)	
1840	Diphenyl ether derivative	C ₂₇ H ₂₈ O ₁₀			<i>Frullania squarrosula</i>	(84)	
1841	Benzaldehyde	C ₇ H ₆ O			<i>Frullania squarrosula</i>	(84)	
					<i>Marsupella emarginata</i>	(17)	
					<i>Radula aquilegia</i>	(223)	
					<i>Radula boryana</i>	(224)	
					<i>Radula lindenbergiana</i>	(223)	
					<i>Radula nudicaulis</i>	(223)	
					<i>Radula wichurae</i>	(223)	
					<i>Asterella</i> (?)	(71)	
1842	3,4-Dimethoxybenzaldehyde	C ₉ H ₁₀ O ₃			<i>Marchantia tosona</i>	(459)	
1843	<i>p</i> -Hydroxybenzaldehyde	C ₇ H ₆ O ₂			<i>Marsupella emarginata</i>	(17)	
1844	Phenylacetaldehyde	C ₈ H ₈ O			<i>Dumortiera hirsuta</i>	(445)	
1845	Dumortin A	C ₁₄ H ₁₀ O ₆			<i>Dumortiera hirsuta</i>	(445)	
1846	Dumortin B	C ₁₄ H ₁₂ O ₆			<i>Dumortiera hirsuta</i>	(445)	
1847	Dumortin C	C ₁₄ H ₁₂ O ₇			<i>Dumortiera hirsuta</i>	(445)	
1848	2-(3,4-Dimethoxyphenethyl)-6-methyl-4-pyrone	C ₁₆ H ₁₈ O ₄			<i>Plagiochila bifaria</i>	(690)	
1849	5-Hydroxy-7-methoxy-2-methylchromone	C ₁₁ H ₁₀ O ₄			<i>Hymenophyton flabellatum</i>	(900)	
1850	2,5-Dihydroxy-7-methoxy-2-methyldihydrochromone	C ₁₁ H ₁₂ O ₅	138-139		<i>Hymenophyton flabellatum</i>	(900)	
1851	5,7-Dimethoxy-2-methylchromone	C ₁₂ H ₁₂ O ₄			<i>Hymenophyton flabellatum</i>	(900)	
1851a	Lichexanthone	C ₁₆ H ₁₄ O ₅			Unidentified <i>Frullania</i> sp.	(426)	
1852	1-(2,4,6-Trimethoxyphenyl)-but-(2 <i>E</i>)-en-1-one	C ₁₃ H ₁₆ O ₄			<i>Hymenophyton flabellatum</i>	(77)	
						(900)	

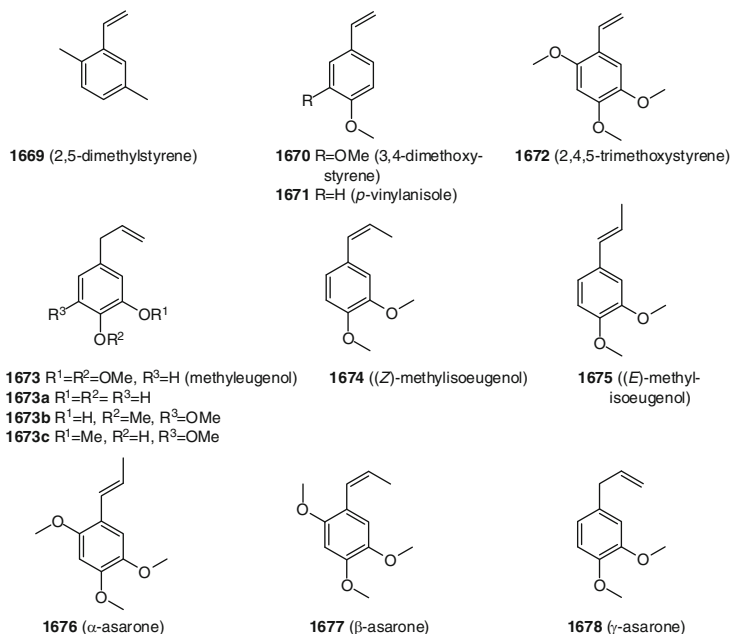
1853	1-(2-Hydroxy-4,6-dimethoxyphenyl)-butan-1,3-dione	C ₁₂ H ₁₄ O ₅		<i>Hymenophyton flabellatum</i>	(900)	
1854	1-(2,4-Dihydroxy-6-methoxyphenyl)-but-(2 <i>E</i>)-en-1-one	C ₁₁ H ₁₂ O ₄	129-131	<i>Hymenophyton flabellatum</i>	(900)	
1855	1-(2-Hydroxy-4,6-dimethoxyphenyl)-(3 <i>R</i>)-hydroxy-1-butanone	C ₁₂ H ₁₆ O ₅	67-68.5	<i>Hymenophyton flabellatum</i>	(900)	X-ray
1856	1-(2-Hydroxy-4,6-dimethoxyphenyl)-but-(2 <i>E</i>)-en-1-one	C ₁₂ H ₁₄ O ₄		<i>Hymenophyton flabellatum</i>	(900)	
1857	1-(2,4,6-Trimethoxyphenyl)-but-(2 <i>Z</i>)-en-1-one	C ₁₃ H ₁₆ O ₄		<i>Hymenophyton flabellatum</i>	(900)	
1858	9-(4-methoxyphenyl)-6-nonen-2-one	C ₁₆ H ₂₂ O ₂		<i>Plagiochila bifaria</i>	(333)	
1859	Tenuiorin	C ₂₈ H ₂₄ O ₁₀	237-238	<i>Bazzania tricenata</i>	(84)	
				<i>Blastia pusilla</i>	(971)	
1860	Methyl evermate	C ₁₈ H ₁₈ O ₇		<i>Frullania nisqualensis</i>	(410)	
				<i>Blastia pusilla</i>	(971)	
1861	Egonol-2-methylbutanoate	C ₂₄ H ₂₆ O ₆		<i>Riccardia multifida</i>	(972)	
1862	Salidroside	C ₁₄ H ₂₀ O ₇		subsp. <i>decrescens</i>		
				<i>Marchantia polymorpha</i>	(634)	
1863	β -(3,4-Dihydroxyphenyl)ethyl- <i>O</i> - β -D-glucoside	C ₁₄ H ₂₀ O ₈		<i>Marchantia polymorpha</i>	(8)	<i>in vitro</i> Culture
1864	Subulatin	C ₃₃ H ₃₄ O ₁₇	-16.8	<i>Jungermannia subulata</i>	(634) (823)	<i>in vitro</i> Culture
1865	(2 <i>R</i>)-Phaselic acid	C ₁₃ H ₁₁ O ₈	-37.7	<i>Lophocolea heterophylla</i>	(823)	
				<i>Scapania parvirecta</i>	(823)	
				<i>Jungermannia subulata</i>	(823)	<i>in vitro</i> Culture

(continued)

Table 4.7 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1866	Pulvic acid methyl ester	C ₁₉ H ₁₄ O ₅			<i>Tylimanthus tenellus</i>	(896)	
1867	Caffeic acid methyl ester	C ₁₀ H ₁₀ O ₄			<i>Pellia epiphylla</i>	(175)	Sporophyte
1868	Ferulic acid methyl ester	C ₁₁ H ₁₂ O ₄			<i>Pellia epiphylla</i>	(175)	Sporophyte
1869	Protocatechuic acid-4- <i>O</i> -β-glucoside	C ₁₃ H ₁₆ O ₉			<i>Lepicolea ochroleuca</i>	(177)	
1870	Vanillic acid-4- <i>O</i> -neohesperidoside	C ₂₀ H ₂₈ O ₁₃			<i>Chandonanthus hirtellus</i> subsp. <i>giganteus</i>	(441)	
1871	Isolespezinic acid	C ₁₅ H ₁₈ O ₉			<i>Plagiochila dusenii</i>	(32)	
1872	Duseninic acid	C ₂₇ H ₃₀ O ₁₆		-26	<i>Plagiochila dusenii</i>	(32)	
1873	5-Heptadeca-(8Z,11Z,14Z)-trienyl-resorcinol monomethyl ether	C ₂₃ H ₃₄ O ₂			<i>Omphalanthus filiformis</i>	(844)	
1874	3-Undecylphenol	C ₁₇ H ₂₈ O			<i>Schistochila appendiculata</i>	(616)	
1875	1,2-Dihydroxy-6-undecylbenzene (=6-undecylcatechol)	C ₁₇ H ₂₈ O ₂			<i>Schistochila appendiculata</i>	(72)	
1876	α-Tocopherol	C ₂₉ H ₅₀ O ₂			<i>Fossombronina alaskana</i>	(268)	
1877	δ-Tocopherol	C ₂₇ H ₄₆ O ₂			<i>Plagiochila circinalis</i>	(635)	
					<i>Jungermannia infusca</i>	(597)	
					<i>Lepidozia spinosissima</i>	(72)	
					<i>Marchantia berteoana</i>	(616)	
					<i>Pellia epiphylla</i>	(176)	

1878	Skatole	C ₉ H ₆ N	<i>Plagiochila ovalifolia</i> <i>Radula marginata</i> <i>Asterella</i> (?) <i>Cyathodium</i> <i>foetidissimum</i> <i>Marchantia polymorpha</i>	(895) (701) (72) (494) (467)
1879	Indole acetic acid	C ₉ H ₇ O ₂ N		
1880	Isotachin A	C ₁₁ H ₁₂ O ₂ S	<i>Isotachis aubertii</i> Unidentified <i>Isotachis</i> sp. I	(288) (73)
1881	Isotachin B	C ₁₂ H ₁₄ O ₂ S	<i>Isotachis aubertii</i> Unidentified <i>Isotachis</i> sp. I Unidentified <i>Isotachis</i> sp. II	(288) (73) (73)
1882	(Z)-Coriandrin	C ₁₀ H ₆ NOS	<i>Balanitopsis cancellata</i> <i>Corsinia coriandrina</i>	(457) (79) (921)
1883	(E)-Coriandrin	C ₁₀ H ₆ NOS	<i>Corsinia coriandrina</i>	(79) (921)
1884	(Z)-O-Methyltridentatol B	C ₁₂ H ₁₅ NOS ₂	<i>Corsinia coriandrina</i>	(79) (921)
1885	(E)-O-Methyltridentatol A	C ₁₂ H ₁₅ NOS ₂	<i>Corsinia coriandrina</i>	(79) (921)
1886	Anthranilic acid	C ₇ H ₇ NO ₂	<i>Metzgeria rufula</i>	(921) (446)
1887	Rufulamide	C ₂₂ H ₂₁ N ₃ O ₉	<i>Metzgeria rufula</i>	(446)



Styrene and phenylpropane derivatives found in the Marchantiophyta

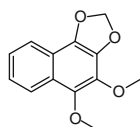
A Malaysian liverwort, identified as either an *Asterella* or *Mannia* species, produced 3,4-dimethoxystyrene (**1670**) (71). The same compound was isolated from the essential oil of *Conocephalum conicum* (543) and a Chinese collection of this same species (487). *Marchesinia* species belonging to the Lejeuneaceae are chemically quite different from other liverworts since they produce simple aromatic compounds with a vinyl group. The Ecuadorian *M. brachiata* was analyzed by GC/MS, leading to the detection of 3,4-dimethoxy-1-vinylbenzene (**1670**), 2,4,5-trimethoxy-1-vinylbenzene (**1672**), and apigenin-7,4'-dimethyl ether (**1913**), which were isolated by subsequent passage over a Sephadex-containing column and medium-pressure liquid chromatography (594). Previously, the presence of eugenol (**1673a**), 4-hydroxy-3,5-dimethoxyallylbenzene (**1673b**) or 3-hydroxy-4,5-dimethoxyallylbenzene (**1673c**), along with the sesquiterpene hydrocarbons, bicyclogermacrene (**293**) and β -caryophyllene (**426**), was suggested by GC/MS analysis of *M. brachiata* collected in Sabah, Malaysia (40, 263). However, the molecular weights and mass spectrometric fragmentation patterns of the compounds assigned to **1673a** and **1673b** or **1673c** were identical to those of **1670** and **1672**. Thus, the previously identified compounds were actually **1670** and **1672**. No differences in secondary metabolite profiles were observed between Dutch, Malaysian, and Ecuadorian samples of *M. brachiata*.

Application of the HS-SPME (head space-solid phase micro extraction) technique coupled to GC/MS analysis was used to detect volatile components of *Drepanolejeunea madagascariensis*, and showed the presence of 4-vinylanisole (**1671**) (247).

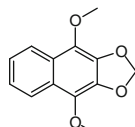
The essential oil from *Marchesinia mackaii* was analyzed by GC and GC/MS. The major components were (*E*)-methylisoeugenol (**1675**) (12–19%), α -asarone (**1676**) (23–31%), β -asarone (**1677**) (11–13%), and γ -asarone (= 2,4,5-

trimethoxyallylbenzene (**1678**) (10–23%), together with the minor components, methyl eugenol (**1673**) and (*Z*)-methylisoeugenol (**1674**) (**220**).

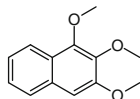
Adelanthus decipiens has been studied chemically and β -barbatene (**235**) and phytosterols were identified (**40**). Further GC/MS and NMR analysis of a CDCl_3 extract of the same liverwort resulted in the detection of three known naphthalenes, wettsteins A (**1679**), B (**1680**), and C (**1681**) (**695**), of which **1680** was the major component. Furthermore, 1,2,4-trimethoxynaphthalene (**1683**) and 1,2,3,4-tetramethoxynaphthalene (**1684**) were detected. Compounds **1679–1681** have been isolated from the New Zealand *Wettsteinia schusterana* and compound **1681** from the Taiwanese *W. inversa*, as mentioned above. *Adelanthus* and *Wettsteinia* belong to the Adelanthaceae family and the finding of the three naphthalenes **1679–1681** in both genera indicates their close relationship. This was the first isolation of **1683** and **1684** in Nature.



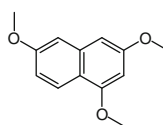
1679 (wettstein A)



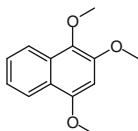
1680 (wettstein B)



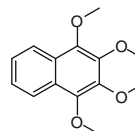
1681 (wettstein C)



1682 (2,4,7-trimethoxynaphthalene)



1683 (1,2,4-trimethoxynaphthalene)

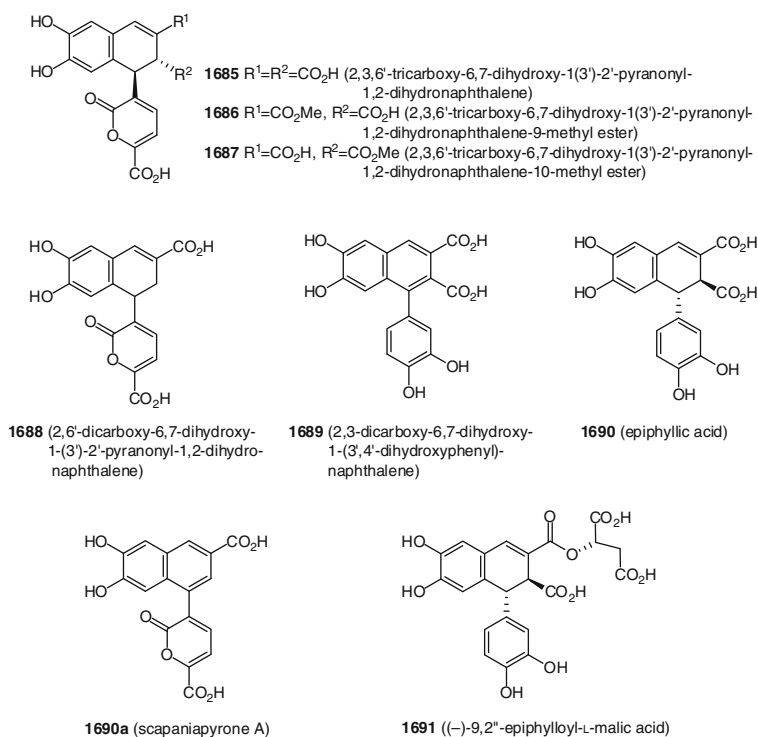


1684 (1,2,3,4-tetramethoxynaphthalene)

Naphthalene derivatives found in the Marchantiophyta

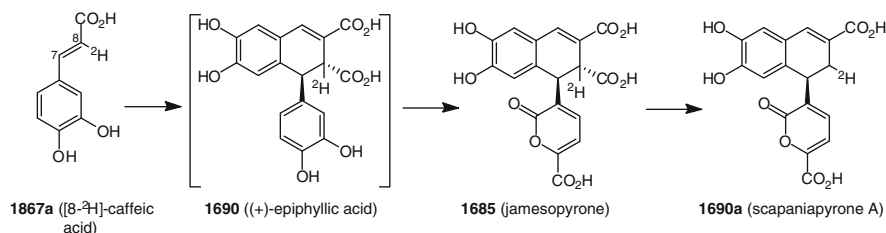
Jamesoniella autumnalis produces not only labdane, clerodane, and *seco*-clerodane diterpenoids, but also lignans. The *n*-butanol-soluble portion of the methanol extract of *in vitro*-cultured *J. autumnalis* was fractionated over Sephadex LH-20, followed by HPLC purification, to afford the five new lignans, 2,3,6'-tricarboxy-6,7-dihydroxy-1(3')-2'-pyranonyl-1,2-dihydronaphthalene (= jamesopyrone) (**1685**), 2,3,6'-tricarboxy-6,7-dihydroxy-1(3')-2'-pyranonyl-1,2-dihydronaphthalene-9-methyl ester (**1686**), 2,3,6'-tricarboxy-6,7-dihydroxy-1(3')-2'-pyranonyl-1,2-dihydronaphthalene-10-methyl ester (**1687**), 2,6'-dicarboxy-6,7-dihydroxy-1(3')-2'-pyranonyl-1,2-dihydronaphthalene (**1688**), and 2,3-dicarboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)naphthalene (**1689**) (**809**). A combination of its IR (3430, 1750, 1645 cm^{-1}), UV (225, 249, 308 nm), and FAB-MS (m/z 389) data, coupled with the comparison of

the ^1H and ^{13}C NMR spectra of the known cyclolignans, 2,3-dicarboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-1,2-dihydronaphthalene (= epiphyllic acid) (**1690**) and its dehydro derivative, scapaniapyrone A (**1690a**), isolated from *Scapania undulata* (**40**), led to the structural determination of the new lignan, **1685**. Further evidence for this structure was based on NOE studies of its permethyl derivative. The *trans*-orientation of the α -pyrone ring and the carboxyl group at C-2 in **1685** was proved by an observed coupling constant of 1.2 Hz between H-1 and H-2 in the permethylated derivative. The complete structures of the other lignans (**1686–1689**) were characterized using the same methods mentioned above. Several cyclolignan derivatives have been isolated from the liverworts. A biogenesis pathway for the formation of **1685** *via* **1690** from caffeic acid is shown in Scheme 4.54 (**819**). Feeding experiments of [$8\text{-}^2\text{H}$]-caffeic acid (**1867a**) in axenic culture cells of *Jamesoniella autumnalis* indicated that the lignans jamesopyrone (**1685**) and scapaniapyrone A (**1690a**) are derived from the coupling of two intact caffeic acid molecules. It was clarified that epiphyllic acid (**1690**) is formed from caffeic acid using a cell-free system of *J. autumnalis* and *Lophocolea heterophylla* (**819**).



Lignans found in the Marchantiophyta

The methanol extract of *Pallavicinia subciliata* was purified by column chromatography to give the two known naphthalene derivatives, 6,7-dihydroxy-



Scheme 4.54 Biosynthesis pathway to scapaniapyrone A (**1690a**)

4-(3,4-dihydroxyphenyl)-naphthalene-2-carboxylic acid (**1689**) and (1*R*,2*S*)-6,7-dihydroxy-1-(3,4-dihydroxyphenyl)-1,2-dihydronaphthalene-2,3-dicarboxylic acid (= epiphylllic acid) (**1690**) (702). These compounds have been isolated from *Pellia epiphylla* and the condensation of two caffeic acid molecules proposed for its biosynthesis (40). The isolation of the precursor **1690** supports the hypothesis of the formation of naphthalene derivative **1689** from two caffeic acids.

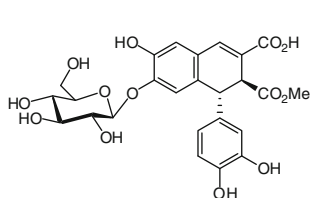
From the cultured cells of *Lophocolea heterophylla*, (–)-epiphylllic acid (**1690**) (40) and 9,2''-epiphyllloyl-malic acid (**1691**) were isolated. The spectroscopic data of **1691** resembled those of **1690**, except for the presence of signals for a malic acid moiety. Long-range coupling between H-2'' and C-9' in the COLOC spectrum was used to demonstrate that the structure of **1691** is 9,2''-epiphyllloylmalic acid (823).

The *n*-butanol-soluble part of the methanol extract of *Lepicolea ochroleuca* was fractionated to give the four new lignans, epiphylllic acid-7-*O*-β-D-glucoside-10-methyl ester (**1692**), epiphylllic acid-7-*O*-β-D-glucoside-10,5'''-*O*-shikimic acid ester (**1693**), epiphylllic acid-7-*O*-β-D-glucoside-9,1''''-*O*-heptitol ester-10,5'''-*O*-shikimic acid ester (**1694**), and epiphylllic acid-9,5'''-*O*-10,5''''-*O*-bis(shikimic acid ester) (**1695**), together with 2,4,6-trihydroxyacetophenone-3,5-di-*C*-glucoside (**1724**) (177), of which the latter compound was isolated also from the liverwort *Scapania nemorea* (253). Proof for all of the structures was carried out by detailed analysis of their HMBC and NOESY NMR spectra.

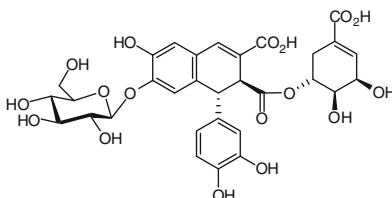
A new lignan, epiphylllic acid-7-*O*-β-D-glucoside-9,6''-*O*-shikimic acid ester-10,4''-*O*-(5''',9'''-*O*-caffeic acid ester)-trilobatinic acid ester (**1696**), was isolated from an ethanol extract of the Chinese liverwort *Lepidozia vitrea* (497). The proposed structure was elucidated by comparison of its spectroscopic data with those of the known epiphylllic acid (**1690**) (183) and analysis of the HMBC and NOESY 2D-NMR spectra.

The chemical constituents of 12 Japanese liverworts have been studied by GC/MS and a number of sesqui- and diterpenoids have been detected. From the ether extract of *Pallavicinia subciliata*, 3-carboxy-6,7-dihydro-1-(3',4'-dihydroxyphenyl)-naphthalene (**1697**) was isolated (882).

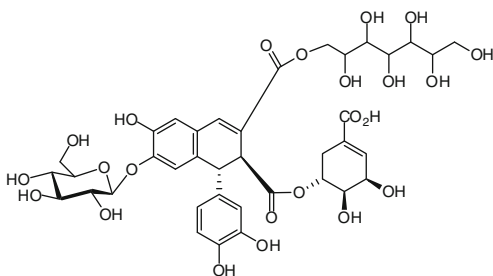
The methanol extract of the Costa Rican *Lepidozia incurvata* was defatted to remove lipophilic compounds by extraction with ether. An ethyl acetate extractive of this residue was found to contain the new 3-carboxy-6-methoxy-1-(3',4'-dihydroxyphenyl)-naphthalene-7-*O*- α -L-rhamnopyranoside (**1712**), together with the previously known 2,3-dicarboxy-6,7-dihydro-1-(3',4'-dihydroxyphenyl)-1,2-dihydronaphthalene (**1690**) and 3-carboxy-6,7-dihydro-1-(3',4'-dihydroxyphenyl)-naphthalene (**1697**) (*183*). These known compounds were isolated earlier from *Pellia endiviifolia* (*180, 682*), and also from *Bazzania trilobata* (*523*), and *Lepidozia reptans* (*705*).



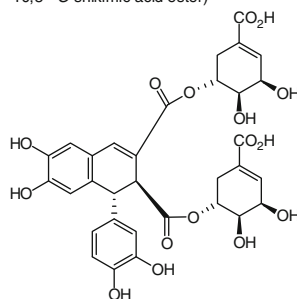
1692 (epiphyllic acid-7-*O*- β -glucoside-10-methyl ester)



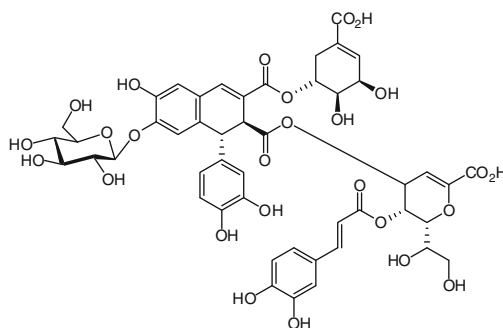
1693 (epiphyllic acid-7-*O*- β -glucoside-10,5''-*O*-shikimic acid ester)



1694 (epiphyllic acid-7-*O*- β -glucoside-9,1'''-*O*-heptitol ester-10,5'''-*O*-shikimic acid ester)

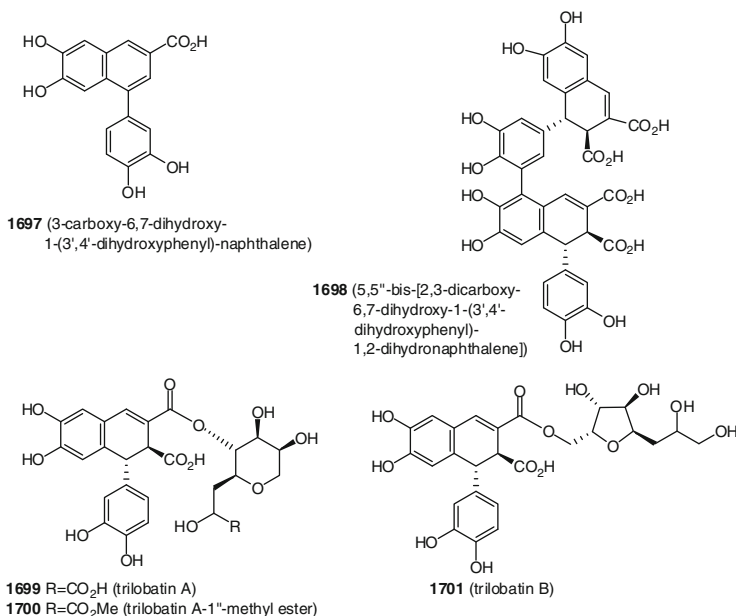


1695 (epiphyllic acid-9,5'''-*O*-10,5'''-*O*-bis(shikimic acid ester))



1696 (epiphyllic acid-7-*O*- β -glucoside-9,6''-*O*-shikimic acid ester-10,4'''-*O*-(5'',9'''-*O*-caffeic acid ester)-trilobatinic acid ester)

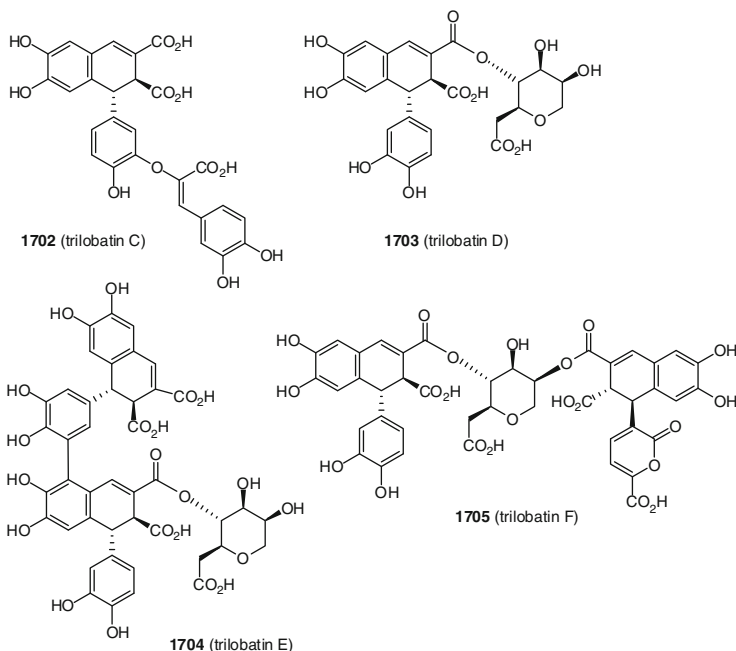
Lignans found in the Marchantiophyta



Lignans found in the Marchantiophyta

Bazzania trilobata produces not only terpenoids but also the new lignans 5,5''-bis-[2,3-dicarboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-1,2-dihydronaphthalene] (**1698**), trilobatin A (**1699**), B (**1701**) and C (**1702**), trilobatin A-1''-methyl ester (**1700**), and bazzania acid (**1711**), together with the previously known lignans, 2,3-dicarboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-1,2-dihydronaphthalene (**1690**) and 3-carboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-1,2-dihydronaphthalene (**1697**) (**523**), which were isolated also from *Pellia epiphylla* (**40**). The structure of **1698** as a symmetrical dimer of **1690** with 5–5'' linked subunits was determined according to its NMR parameters inclusive of the HMBC and NOESY spectra. The presence of a phenyldihydronaphthalene moiety and a 2-hydroxy-3-(3',4',5'-trihydroxytetrahydropyran-2-yl)propionic acid subunit in trilobatin A (**1699**) was confirmed from its COSY and HMBC spectra as well as the molecular ion peak at m/z 563. The linkages proposed for both subunits were based on the analysis of a HMBC experiment, which showed a correlation with the carboxylic carbon at C-9 of the lignan moiety. The sterically fixed *trans*-arrangement of H-5'' was confirmed by the coupling constant ($J = 9.6$ Hz) with the H-4'' proton resonance, and the *equatorial* orientation of H-7'' and H-6'' was assigned from the small coupling constant ($J = 3.4$ Hz) observed. Compound **1700** was assigned readily as trilobatin A-1'' methyl ester by FAB-MS and from an upfield shift of the C-1'' carboxyl signal of 1.4 ppm. The structure of **1702** was arrived at by comparison of the NMR spectra of **1699** with those of **1702**, and by analysis of the 2D-NMR data of the side chain residue, a 4'-[1,2-dihydroxypropenyl-5,6-dihydroxy-7''-methyleneoxytetrahydrofuran] moiety, esterified with the carboxylic acid at C-9 of a 2,3-dicarboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-1,2-

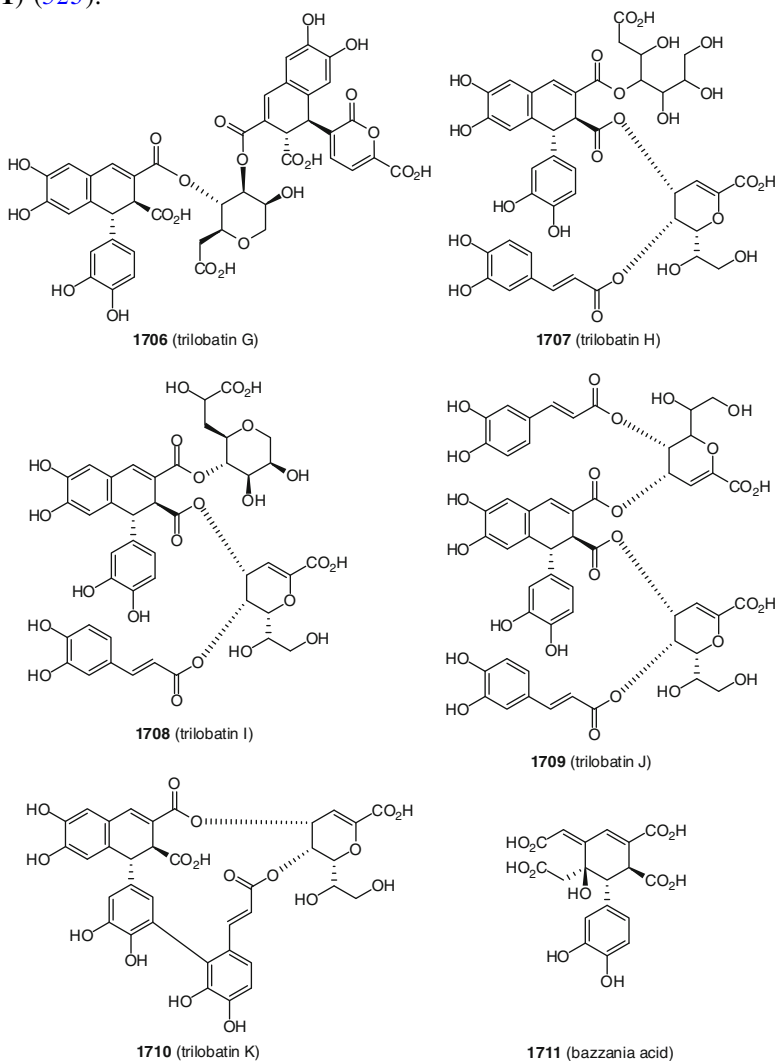
dihydronaphthalene (**1690**) unit. The presence of 2,3-dicarboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-1,2-dihydronaphthalene and an 8-*O*-substituted caffeic acid moiety was based on the analysis of the COSY and HMBC spectra. Methylation of **1702** gave an octamethyl derivative inclusive of three carboxymethyl groups. Therefore, C-8'' of the caffeic moiety was proposed as being connected to C-3' of the lignan subunit *via* an ether linkage, with this inference confirmed using a HMBC experiment (**523**).



Lignans found in the Marchantiophyta

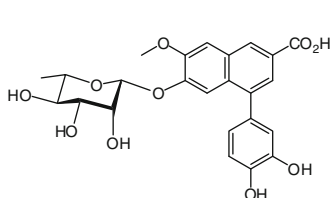
The molecular structure and relative configuration of **1711** were determined by comparison of its spectroscopic data with those of **1690** and from the ^{13}C NMR spectrum. The latter showed 18 signals, of which four were carboxylic, ten due to aromatic carbons, and four due to aliphatic carbons, including one quaternary, oxygen-bearing carbon atom. COSY and HMBC experiments showed the complete constitution of **1711**, demonstrating it to be an oxidation product of **1690**. The relative configuration was established by a NOESY experiment and the coupling constant observed between H-1 and H-2 ($J = 11.3$ Hz) in its ^1H NMR spectrum, and suggested a quasi-*equatorial* relationship of the carboxylic acid group at C-10 and the aryl substituent of C-1. *Bazzania* acid (**1711**) might be formed from **1690**. Oxidative cleavage of the ene-diol structure of **1690** by intradiol dioxygenase could lead to the formation of two carboxyl functions whereby the geometry of the remaining double bonds is retained. The subsequent addition of water, proceeding in a

Markownikow-orientation, would lead to the formation of bazzania acid (**1711**) (523).

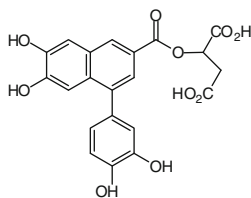


Lignans found in the Marchantiophyta

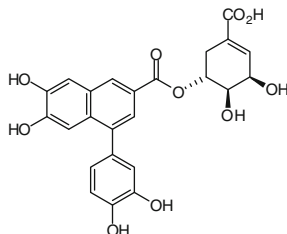
Further fractionation of the methanol extract of *Bazzania trilobata* resulted in the isolation of eight new lignans, named trilobatins D-K (**1703–1710**), along with the known jamesopyrone (**1685**) (713) which was isolated from the liverwort *Jamesoniella autumnalis* (809). The structures of the new compounds were based on their NMR and ESI mass spectrometric data. The key structure and parent compound of these lignans is epiphylllic acid (**1690**), derived from two caffeic acid moieties (713).



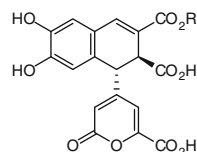
1712 (3-carboxy-6-methoxy-1-(3',4'-dihydroxyphenyl)-naphthalene-7-O- α -L-rhamnopyranoside)



1713 (3-carboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-naphthalene-9,2''-O-malic acid ester)

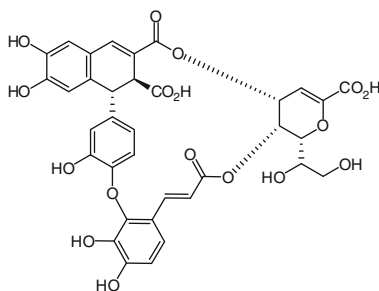


1714 (3-carboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-naphthalene-9,5''-O-shikimic acid ester)



1715 R=H (erimopyrone)

1716 R=Me (erimopyrone-9-methyl ester)



1717 (pelliatin)

Lignans found in the Marchantiophyta

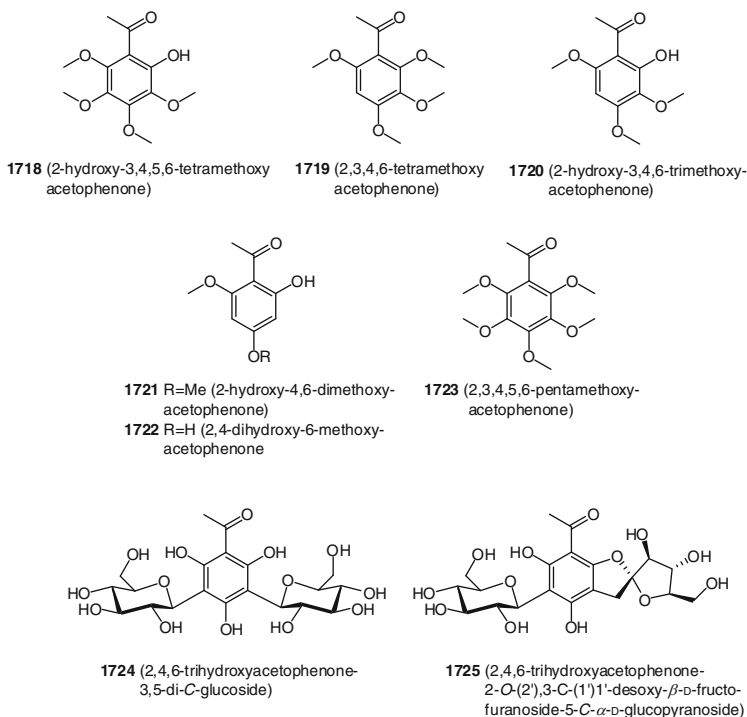
Ethyl acetate extracts of the German *Chiloscyphus polyanthos* and the Swiss *Jungermannia exsertifolia* furnished the known lignans **1690** and **1697** and the new 3-carboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-naphthalene-9,2''-O-maleic acid ester (**1713**) and 3-carboxy-6,7-dihydroxy-1-(3',4'-dihydroxyphenyl)-naphthalene-9,5''-O-shikimic acid (**1714**) ([183](#)). These new structures were based on HMBC analysis and comparison with published spectroscopic data of **1689** and **1690**, which have been found in *Jamesoniella autumnalis* ([809](#)) and *Bazzania trilobata* ([523](#)).

The ethyl acetate-soluble portion of the methanol extract of *Moerckia erimona* was passed through a Sep-Pak C₁₈ cartridge and further purified by HPLC to afford two new lignans named erimopyrone (**1715**) and erimopyrone 9-O-methyl ester (**1716**), for which their structures were elucidated by the analysis of 2D-NMR spectra ([820](#)). The permethylated derivative of **1715** is the isomer of permethylated jamesopyrone (**1685**), from the liverwort *Jamesoniella autumnalis* ([809](#)).

A methanol extract of *Pellia epiphylla* was found to contain a new macrocyclic lignan, pelliatin (**1717**). Methylation of **1717** gave a heptamethylated product, and the structure of pelliatin was proved by the careful analysis of the 2D-NMR (^1H - ^1H COSY, HMBC and ROESY spectra) of this methylated product. The C-8 moiety of **1717** might be derived from 3,4-dihydroxycinnamic alcohol, opened by an extradiol dioxygenase, with the formyl group then cleaved, the two remaining double bonds undergoing epoxidation, followed by hydration and ring closure, to give a semi-acetal, from which the C-8 unit is formed after elimination of water (**181**). A similar biogenesis was proposed for the formation of scapaniapyrone A (**1690a**) from *Scapania undulata* (**556**) and *Jamesoniella autumnalis* (**819**).

An ethanol extract of the New Zealand *Plagiochila fasciculata* was fractionated on a C_{18} phase to afford the two acetophenones, 2-hydroxy-3,4,6-trimethoxyacetophenone (**1720**) and 2-hydroxy-4,6-dimethoxyacetophenone (**1721**) (**481**). Nagashima and coworkers confirmed the presence of these acetophenones in the same New Zealand specimen of *P. fasciculata* (**607**). The essential oil of the higher plant *Croton* aff. *nepetifolius* belonging to the family, Euphorbiaceae, produces **1721** (**171**). Compound **1721** is distributed in many other higher plants, as, for example, in the genus *Artemisia* belonging to the Asteraceae. On the other hand, the liverwort *Trocholejeunea sandvicensis* belonging to the Lejeuneaceae produces similar hydroxy acetophenones (**40**) although **1721** and **1720** have not yet been isolated. There are two chemotypes of the New Zealand *P. fasciculata*: one elaborates the acetophenones **1720** and **1721** as major components, while the other produces mainly anastreptene (**122**) and 3-methoxy-4'-hydroxybibenzyl (**1482**) (**72**). The second chemotype is very closely related chemically to *P. stephensoniana*, since the latter produces 3-methoxy-4'-hydroxybibenzyl (**1482**) and α -terpinene (**13**) as the major components.

Rycroft (**688**) and Rycroft and coworkers (**692**, **695**) reported the structural elucidation of compounds of certain liverworts by working with the crude extracts themselves rather than by devoting laboratory resources and time towards isolating the compounds individually. For this work, the lipophilic constituents of a small amount of each liverwort were extracted with the NMR solvent CDCl_3 . This technique was applied to analysis of the chemical constituents of the British liverworts *Adelanthus decipiens* (collected from different locations) and *Cryptothallus mirabilis*. The detection of 2-hydroxy-3,4,5,6-tetramethoxyacetophenone (**1718**), 2,3,4,6-tetramethoxyacetophenone (**1719**), wettsteins A (**1679**) and B (**1680**), 1,2,3-trimethoxynaphthalene (**1681**), 1,2,4-trimethoxynaphthalene (**1683**), 1,2,3,4-tetramethoxynaphthalene (**1684**), 2-hydroxy-3,4,6-trimethoxyacetophenone (**1720**), 2-hydroxy-4,6-dimethoxyacetophenone (**1721**), and 2,3,4,5,6-pentamethoxyacetophenone (**1723**) was confirmed by this method in *A. decipiens* (**695**). The European and South American populations of *Adelanthus decipiens* have not diverged greatly and display only minor infraspecific variations. This is the first record of compounds **1718**, **1719**, and **1723** as natural products. Furthermore, 2-hydroxy-3,4,6-trimethoxyacetophenone (**1720**) and 2,3,4,5,6-pentamethoxyacetophenone (**1723**) were isolated from the CDCl_3 extracts and their structures were elucidated using the GC and NMR data obtained (**695**). The presence of 15-acetoxypinguisone (**858**) has been confirmed using the above-mentioned methodology for *C. mirabilis* (**688**, **692**).



Acetophenone derivatives found in the Marchantiophyta

Fractionation of the ether extract of an unidentified New Zealand *Heteroscyphus* species led to the isolation of the known 2,4-dihydroxy-6-methoxyacetophenone (**1722**) (635), which has been found previously in the higher plant, *Rugelia nudicaulis* (122).

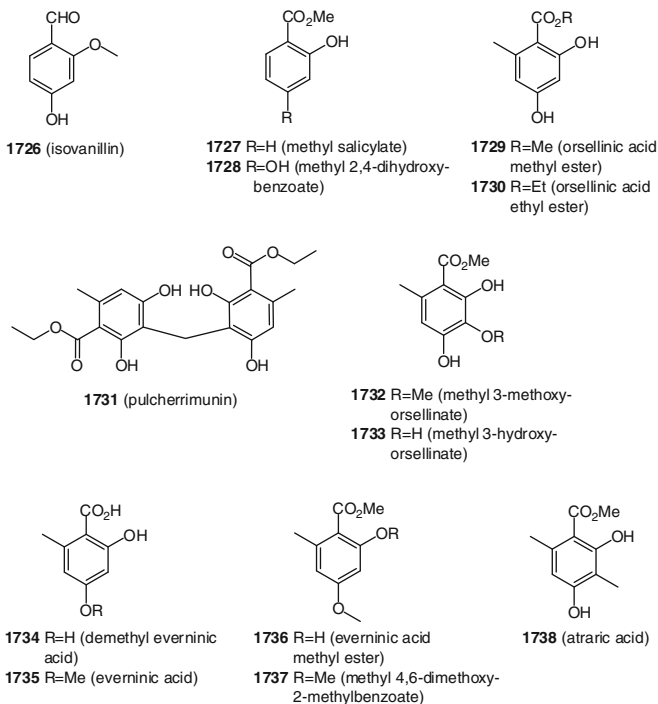
The rare acetophenone, **1725**, together with an unusual spiroacetal and 2,4,6-trihydroxyacetophenone-3,5-di-C-glucoside (**1724**), were isolated from a methanol extract of the Patagonian *Adelanthus lindenbergianus*. Their structures were deduced from the 2D-NMR data including the NOE spectrum (116). The volatile components of *Chandonanthus hirtellus* were analyzed and the presence of methyl salicylate (**1727**) was demonstrated (494).

The Chinese *Ptilidium pulcherrimum*, when collected at an altitude of 4,000 m, elaborated the known 2-hydroxy-3,4,6-trimethoxyacetophenone (**1720**), isovanillin (**1726**), methyl 2,4-dihydroxybenzoate (**1728**), orsellinic methyl ester (**1729**), ethyl orsellinate (**1730**), and a new dimeric product named pulcherrimumin (**1731**). The structure of the latter compound was established by interpretation of its 2D-NMR data, inclusive of the HMBC spectrum (271). Orsellinic acid methyl ester (**1729**) was also isolated from *Blasia pusilla* as a minor constituent (971). Orsellinic acid derivatives have been isolated from lichen sources previously (359). These compounds may actually be constituents of the symbiotic *Nostoc* species that co-occur with this liverwort.

Methyl 3-methoxyorsellinate (**1732**), methyl 3-hydroxyorsellinate (**1733**), demethyl everninic acid (**1734**), eveninic acid (**1735**), methyl lecanorate (**1839**), and the new diphenyl ether **1840**, which might originate from **1734**, were isolated from the New Zealand *Frullania squarrosula* (**84**). Compounds **1732**, **1733**, **1735**, and **1839** are known to be produced by lichens (**359**). These aromatic compounds should be genuine components of *F. squarrosula*, since any plant impurities from the specimens investigated chemically were carefully removed before extraction.

Blasia pusilla elaborates everninic acid methyl ester (**1736**) along with bis-bibenzyls and bis-bibenzyl dimers, as mentioned earlier (**971**). The essential oils of four *Plagiochila* species were analyzed by GC and GC/MS. Among these, *Plagiochila stricta* elaborated not only bicyclogermacrene (**293**) but also methyl everminate (= methyl 2-hydroxy-4-methoxy-6-methyl benzoate) (**1736**) as major components (**221**). The essential oil of *Plagiochila bifaria* was analyzed by GC and GC/MS to identify methyl everminate (**1736**) as a major component (**277**, **333**).

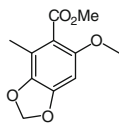
Plagiochila killarniensis was extracted with CDCl_3 and the crude extract analyzed by GC/MS to detect the previously known methyl everminate (**1736**) and its methyl ether (**1737**), methyl 2,4,5-trimethoxy-6-methylbenzoate (**1741**), and methyl 6-methoxy-2-methyl-3,4-methylenedioxybenzoate (**1739**). Comparison of its spectroscopic data with those of **1739** was used to confirm the structure of methyl 6-hydroxy-2-methyl-3,4-methylenedioxybenzoate (**1740**). Methyl everminate is known as an odoriferous component of oak moss, as for example from the lichen *Evernia prunastri*. Compound **1736** might be responsible of the musty smell of *P. killarniensis* (**696**).



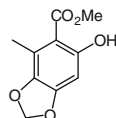
Benzaldehyde and benzoic acid derivatives found in the Marchantiophyta

Fractionation of the Argentinean *Frullania brasiliensis* led to the isolation of the previously known atraric acid (= methyl 2,4-dihydroxy-3,3,5-dimethylbenzoate) (**1738**) (98).

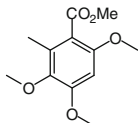
Further fractionation of the ether and methanol extracts of the British *Plagiochila spinulosa* resulted in the isolation of two new benzoates, methyl 6-methoxy-2-methyl-3,4-methylenedioxybenzoate (**1739**) and methyl 3,4,6-trimethoxy-2-methylbenzoate (**1741**), for which their structures were established with the aid of HMBC NMR spectra (165). The presence of the same benzoates in the Belgian *P. spinulosa* and *P. killarniensis* was confirmed by the groups of Connolly (165) and Rycroft (696). The two highly oxygenated benzoates **1739** and **1742** were isolated from the ether extract of the British *Plagiochila spinulosa*. Compound **1742** was assigned as methyl 2,3,5-trimethoxy-6-methyl benzoate by HMBC and NOESY NMR experiments (617). Compounds **1739** and **1741** have been isolated from or detected in the same British species (40) and **1739** and **1740** detected in many other *Plagiochila* species (221).



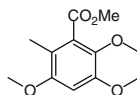
1739 (methyl 6-methoxy-2-methyl-3,4-methylenedioxybenzoate)



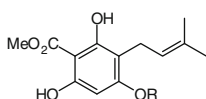
1740 (methyl 6-hydroxy-2-methyl-3,4-methylenedioxybenzoate)



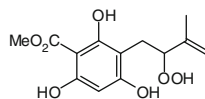
1741 (methyl 3,4,6-trimethoxy-2-methylbenzoate)



1742 (methyl 2,3,5-trimethoxy-6-methylbenzoate)



1743 R=Me (methyl 2,6-dihydroxy-3-(3-methyl-2-butenyl)-4-methoxybenzoate)
1744 R=H (methyl 2,4,6-trihydroxy-3-(3-methyl-2-butenyl)benzoate)



1745 (methyl 2,4,6-trihydroxy-3-(2-hydroperoxy-3-methyl-3-butenyl)benzoate)

Methyl benzoate derivatives found in the Marchantiophyta

Pedinophyllum species belonging to the Plagiochilaceae are very rare liverworts. The dichloromethane extract of the Scottish *P. interruptum* was fractionated to give three new prenylated benzoic acid methyl esters, namely, methyl 2,6-dihydroxy-4-methoxy-3-(3-methyl-2-butenyl)benzoate (**1743**), methyl 2,4,6-trihydroxy-3-(3-methyl-2-butenyl)benzoate (**1744**), and methyl 2,4,6-trihydroxy-3-(2-hydroperoxy-3-methyl-3-butenyl)benzoate (**1745**), as determined using 2D-NMR spectroscopy. Compound **1744** proved to be very unstable, and, upon exposure to the atmosphere, it rapidly converted into the hydroperoxy product **1745** (214).



Fig. 4.26 *Trichocolea pluma*

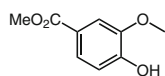
The ether extract of *Trichocolea pluma* (Fig. 4.26) collected in Borneo and Tahiti was analyzed by GC/MS to detect trichocolein (**1747**), tomentellin (**1748**), and isotomentellin (**1749**). Both collections also produce vanillic acid methyl ester (**1746**), which was obtained for the first time from the liverworts ([490](#), [494](#)).

The ethanol extract of the New Zealand *Trichocolea mollissima* was fractionated to give methyl 4-[(2*E*)-3,7-dimethyl-5-oxo-2,6-octadienyl]oxy]-3-methoxybenzoate (= tomentellin) (**1748**), methyl 4-[(3*Z*)-3,7-dimethyl-5-oxo-3,6-octadienyl]oxy]-3-methoxybenzoate (= (*E*)-isotomentellin) (**1749**), and methyl 4-[(3*Z*)-3,7-dimethyl-5-oxo-3,6-octadienyl]oxy]-3-methoxybenzoate (= (*Z*)-isotomentellin) (**1750**). Repeated fractionation of the ether extract of the Japanese *Trichocolea tomentella* resulted in the isolation of **1748**, **1750**, and methyl 4-[(2*Z*)-3,7-dimethyl-2,6-octadienyl]oxy]-3-methoxybenzoate (= deoxytomentellin) (**1751**), and methyl 4-[(2*E*)-3,7-dimethyl-3-oxo-2,6-octadienyl]oxy]-3-hydroxybenzoate (= demethoxytomentellin) (**1752**). The ethanol extract of the New Zealand *Trichocolea lanata* was subjected to flash column chromatography over C₁₈ reversed-phase silica gel to give methyl 4-(3-methyl-2-butenoxy)-3-methoxybenzoate (= trichocolein) (**1747**). The previous compounds **1747**–**1749**, **1751**, and **1752** were assigned initially as prenyl esters ([39](#), [40](#)). However, these structures have been revised using 2D-NMR spectroscopy (HMQC, HMBC, and NOE difference experiments), and as a result of the synthesis of trichocolein (**1747**) by etherification of 4-bromo-2-methylbut-2-ene with methyl 3-methoxy-4-hydroxybenzoate ([616](#), [653](#)).

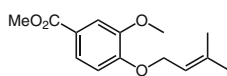
Barlow and associates studied the incorporation of [1-¹³C] glucose into trichocolein (**1747**) and deoxytomentellin (**1751**), as biosynthesized in the liverwort, *Trichocolea tomentella*, and established that the isoprene units of the hemi- and monoterpene moieties of these compounds are derived through the methyl-erythritol phosphate pathway ([99](#)). During a biosynthetic study of the prenyl ether constituents of

Trichocolea tomentella, an additional compound, peroxytomentellin (**1753**), was isolated, with its structure characterized by 2D-NMR spectroscopic analysis (99).

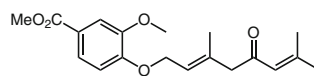
The three naturally occurring tomentellins, **1748**, **1751**, and **1754**, which were isolated from *Trichocolea tomentella* and *T. hatcheri*, were synthesized by Baek and coworkers (90). Methyl vanillate was reacted with 8-chloro-2,6-dimethyl-2,6-octadien-4-ol and sodium hydride in dry DMF to yield methyl [(5-hydroxygeranyl)-4-oxo]-3,4-dimethylbenzoate, followed by oxidation by pyridinium chlorochromate–alumina to yield methyl 4[(2*E*)-3,7-dimethyl-5-oxo-2,6-octadienyl]oxy-3-methoxybenzoate (**1748**). Methyl vanillate was reacted with geranyl bromide to afford methyl 4[(2*E*)-3,7-dimethyl-2,6-octadienyl]oxy-3-methoxybenzoate (**1751**). Treatment of geranyl bromide and methyl 3,4-dihydroxybenzoate yielded methyl 4[(2*E*)-3,7-dimethyl-5-oxo-2,6-octadienyl]oxy-3-hydroxybenzoate (**1754**), together with methyl 3,4-digeranyloxybenzoate and methyl 3-geranyloxy-4-hydroxybenzoate (90).



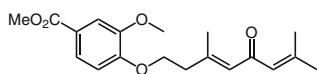
1746 (vanillic acid methyl ester)



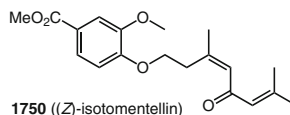
1747 (trichocolein)



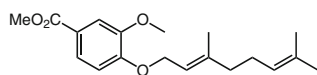
1748 (tomentellin)



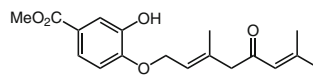
1749 (tomentellin)



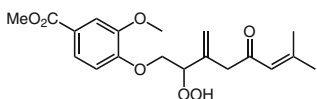
1750 ((*Z*)-isotomentellin)



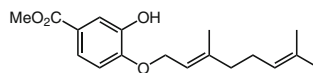
1751 (deoxytomentellin)



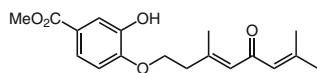
1752 (demethoxytomentellin)



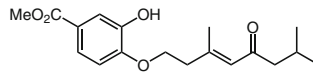
1753 (isohydroperoxytomentellin)



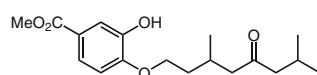
1754 (methyl 4-[(2*E*)-3,7-dimethyl-2,6-octadienyl]oxy-3-hydroxybenzoate)



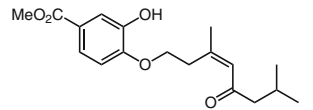
1755 (methyl 4-[(3*E*)-3,7-dimethyl-5-oxo-3,6-octadienyl]oxy-3-hydroxybenzoate)



1756 (methyl 4-[(3*E*)-3,7-dimethyl-5-oxo-3-octenyl]oxy-3-hydroxybenzoate)



1757 (methyl 4-[(3,7-dimethyl-5-oxo-octyl]oxy-3-hydroxybenzoate)



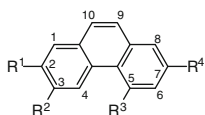
1758 (methyl 4-[(3*Z*)-3,7-dimethyl-5-oxo-3-octenyl]oxy-3-hydroxybenzoate)

Methyl benzoate and its prenyl ether derivatives found in the Marchantiophyta

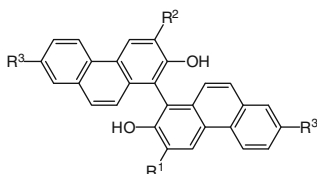
The ethanol- and chloroform-soluble extracts of the New Zealand *Trichocolea hatcheri* showed cytotoxic effects against monkey kidney cells. The combined extracts were fractionated by reversed-phase flash chromatography to yield methyl 4-[(2*E*)-3,7-dimethyl-2,6-octadienyl]oxy-3-hydroxybenzoate (**1754**), methyl 4-[(3*E*)-3,7-dimethyl-5-oxo-3,6-octadienyl]oxy-3-hydroxybenzoate (**1755**), methyl 4-[(3*E*)-3,7-dimethyl-5-oxo-3-octenyl]oxy-3-hydroxybenzoate (**1756**), methyl 4-[(3*E*)-3,7-dimethyl-5-oxo-octyl]oxy-3-hydroxybenzoate (**1757**), and methyl 4-[(3*Z*)-3,7-dimethyl-5-oxo-3-octenyl]oxy-3-hydroxybenzoate (**1758**), together with the known methyl 4-[(2*E*)-3,7-dimethyl-5-oxo-2,6-octadienyl]oxy-3-methoxybenzoate (**1748**) and methyl 4-[(3*Z*)-3,7-dimethyl-5-oxo-3,6-octadienyl]oxy-3-methoxybenzoate (**1749**). All of these new compounds have a free hydroxy group at C-3' on the benzene ring. The structure of **1754** was assigned by comparison of its spectroscopic data with those of demethoxytomentellin (**1752**) and as a result of the observation of a NOE correlation between the H-5' signal and the H-1 protons of the geranyl group. The structures of the other compounds were identified by comparison of their spectroscopic data with those of **1754** and by careful analysis of each NMR spectrum (91).

Previously, two dihydrophenanthrenes and three phenanthrenes have been isolated from the genera *Plagiochila* and *Riccardia*, and from *Marchantia paleacea* var. *diptera* (40). Since 1995, 26 phenanthrene derivatives were obtained from *Plagiochila* species belonging to the Jungermanniales and *Marchantia* species from the Marchantiales. The occurrence of phenanthrenes is very rare among Metzgeriales species.

The methanol extract of *M. paleacea* var. *diptera* was fractionated to afford a new trihydroxyphenanthrene (**1759**), which was methylated to give a trimethoxy derivative with spectroscopic data identical to those of 2,3,7-trimethoxyphenanthrene prepared from 2-hydroxy-3,7-dimethoxyphenanthrene (**1763**). Thus, the structure of this new phenanthrene was assigned as 2,3,7-trihydroxyphenanthrene (**1759**) (436). Compound **1763** was isolated earlier from the Indian *Marchantia polymorpha* (40).



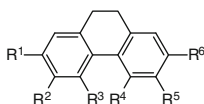
- 1759** R¹=R²=R⁴=OH, R³=H
(2,3,7-trihydroxyphenanthrene)
1760 R¹=R²=OMe, R³=H, R⁴=OH
(2,3-dimethoxy-7-hydroxyphenanthrene)
1761 R¹=R⁴=OH, R²=OMe, R³=H
(2,7-dihydroxy-3-methoxyphenanthrene)
1762 R¹=OH, R²=R³=OMe, R⁴=H
(2-hydroxy-3,5-dimethoxyphenanthrene)
1763 R¹=OH, R²=R⁴=OMe, R³=H
(2-hydroxy-3,7-dimethoxyphenanthrene)
1764 R¹=R³=OMe, R²=OH, R⁴=H
(3-hydroxy-2,5-dimethoxyphenanthrene)
1765 R²=OH, R¹=R⁴=OMe, R³=H
(3-hydroxy-2,7-dimethoxyphenanthrene)



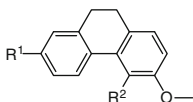
- 1766** R¹=R²=OMe, R³=OH
(3,3'-dimethoxy-2,2',7,7'-tetrahydroxy-1,1'-biphenanthrene)
1767 R¹=OMe, R²=R³=OH
(3-methoxy-2,2',3',7,7'-pentahydroxy-1,1'-biphenanthrene)
1768 R¹=R²=R³=OH
(2,2',3,3',7,7'-hexahydroxy-1,1'-biphenanthrene)

The methanol extract of sterile cultures of *Marchantia polymorpha* was purified by column chromatography and HPLC to afford the two phenanthrenes, **1760** and **1761**, and the three biphenanthrenes, **1766**, **1767**, and **1768** (8). The structure of **1760** was established as 2,3-dimethoxy-7-hydroxyphenanthrene by comparison of its ^1H NMR spectrum with that of 2-hydroxy-3,7-dimethoxyphenanthrene previously isolated from *M. polymorpha* (40). Examination of the NOE spectrum was used to confirm the location of the two methoxy groups at C-2 and C-3 in **1760**. Evidence to support the proposed structure of 2,7-dihydroxy-3-methoxyphenanthrene (**1761**) was obtained after the analysis of the spectroscopic data in comparison of those of **1760**, and also as a result of a NOE experiment. The dimeric structure of **1766** was deduced by the molecular formula obtained by CIMS (m/z 479.2) and NMR evidence for the symmetrical coupling of two molecules of the phenanthrene **1761**. The location of the methoxy group and the position of the aromatic proton were based on NOE experiments of the tetramethyl ether prepared from **1766** by methylation with methyl iodide. The ^1H NMR spectrum of **1767** showed this compound to be a non-symmetrical dimeric 1,1'-coupled phenanthrene with a 1,2,3,7,1',2',3',7'-substitution pattern, from the presence of two sets of six aromatic proton signals. The position of a methoxy group at C-3 was assigned by a NOE experiment. Conclusive evidence to support the proposed structure was obtained from the formation of tetramethyl ether having spectroscopic data identical to those of tetramethyl ether prepared from **1766**. Thus, the structure of **1767** was established as 3-methoxy-2,7,2',3',7'-pentahydroxy-1,1'-biphenanthrene. The ^1H NMR spectrum of **1768** was also similar to that of **1766**, except for the absence of a methoxy group, suggesting that **1768** might be the dimethyl bis-phenanthrene of **1766**. This inference was confirmed by the preparation of the same tetramethyl ether from **1768** by methylation (8).

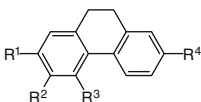
Anton and co-workers reported the presence of 2-hydroxy-3,5-dimethoxyphenanthrene (**1762**) in *Plagiochila permista* var. *integerrima* (33). Its 9,10-dihydro derivative **1770** was also isolated from this species and also from *P. bifaria* (277), *P. killarniensis* (696), *P. retrorsa* (698), and *P. stricta* (699). Further study on the ether extract of *Marchantia tosana* and *Marchantia paleacea* var. *diptera* collected in different locations gave the phenanthrene derivative **1764** from the former species, along with 2-hydroxy-3,7-dimethoxyphenanthrene (**1763**) from *Marchantia paleacea* var. *diptera* (436). Previously, 2,5-dimethoxy-3-hydroxyphenanthrene (**1764**) and marchantin-type bis-bibenzyls have been isolated from *M. tosana* (40), but such aromatic compounds were not found in *M. tosana* investigated by Konoshima. It is suggested that *M. tosana* occurs as two chemotypes in Japan. 2,7-Dimethoxy-3-hydroxyphenanthrene (**1765**) has been isolated from the Japanese *Marchantia tosana* and its structure was determined mainly by 2D-NMR experiments (459). The Japanese *Riccardia multifida* was reinvestigated chemically to give 3,4-dimethoxy-5-hydroxy-9,10-dihydrophenanthrene (**1769**) (583), which has been isolated from *R. jackii* (526).



- 1769** $R^2=R^3=OMe$, $R^4=OH$, $R^1=R^5=R^6=H$
(5-hydroxy-3,4-dimethoxy-9,10-dihydrophenanthrene)
1770 $R^1=OH$, $R^2=R^4=OMe$, $R^3=R^5=R^6=H$
(2-hydroxy-3,5-dimethoxy-9,10-dihydrophenanthrene)
1771 $R^1=R^2=OMe$, $R^4=OH$, $R^3=R^5=R^6=H$
(5-hydroxy-2,3-dimethoxy-9,10-dihydrophenanthrene)
1772 $R^1=R^2=R^4=OMe$, $R^3=R^5=R^6=H$
(2,3,5-trimethoxy-9,10-dihydrophenanthrene)
1773 $R^1=OH$, $R^2=R^6=OMe$, $R^3=R^4=R^5=H$
(2-hydroxy-3,7-dimethoxy-9,10-dihydrophenanthrene)
1774 $R^1=R^2=R^4=OMe$, $R^3=R^5=R^6=H$
(2,3,7-trimethoxy-9,10-dihydrophenanthrene)
1775 $R^1=R^5=OMe$, $R^4=OH$, $R^2=R^3=R^6=H$
(5-hydroxy-2,6-dimethoxy-9,10-dihydrophenanthrene)
1776 $R^2=OMe$, $R^3=R^4=OH$, $R^1=R^5=R^6=H$
(4,5-dihydroxy-3-methoxy-9,10-dihydrophenanthrene)
1777 $R^1=R^4=R^5=OH$, $R^2=R^6=OH$, $R^3=OH$
(4-hydroxy-3,7-dimethoxy-9,10-dihydrophenanthrene)
1778 $R^1=R^5=R^6=H$, $R^2=R^4=OH$, $R^3=Me$
(3,5-dihydroxy-4-methoxy-9,10-dihydrophenanthrene)
1779 $R^1=R^2=R^4=R^6=OMe$, $R^3=R^5=H$
(2,3,5,7-tetramethoxy-9,10-dihydrophenanthrene)



- 1780** $R^1=R^2=OMe$
(2,5,6-trimethoxy-9,10-dihydrophenanthrene)
1781 $R^1=R^2=OH$
(2,5-dihydroxy-6-methoxy-9,10-dihydrophenanthrene)
1782 $R^1=OH$, $R^2=OMe$
(2-hydroxy-5,6-dimethoxy-9,10-dihydrophenanthrene)



- 1783** $R^1=R^2=R^3=R^4=OMe$
(2,3,4,7-tetramethoxy-9,10-dihydrophenanthrene)
1784 $R^1=R^2=R^4=OH$, $R^3=OMe$
(2,3,7-trihydroxy-4-methoxy-9,10-dihydrophenanthrene)
1785 $R^1=OH$, $R^2=R^3=R^4=OMe$
(2-hydroxy-3,4,7-trimethoxy-9,10-dihydrophenanthrene)

Dihydrophenanthrene derivatives found in the Marchantiophyta

Anton and associates (33) studied the chemical constituents of an unidentified Costa Rican *Plagiochila* species (identified later as *P. permista* var. *integerrima*) (34), to isolate the new 2-hydroxy-3,5-dimethoxyphenanthrene (1770), 2,3-dimethoxy-5-hydroxyphenanthrene (1771), 2,3,5-trimethoxyphenanthrene (1772), 2-hydroxy-3,7-dimethoxyphenanthrene (1773), 2,3,7-trimethoxyphenanthrene (1774), 2,6-dimethoxy-5-hydroxyphenanthrene (1775), and 4,5-dihydroxy-3-methoxyphenanthrene (1776), along with the known 2,3,5,7-tetramethoxyphenanthrene (1779) (500). The position of each functional group on the benzene rings in the new compounds was elucidated by means of HMQC, HMBC, and NOESY NMR experiments. The substitution patterns of the phenanthrene 1771 were identical to those of 1770 on the basis of the analytical methods mentioned above (33).

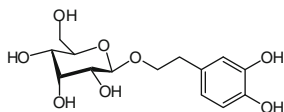
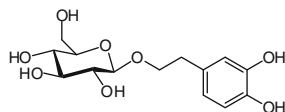
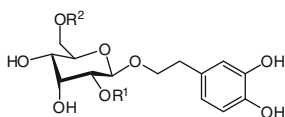
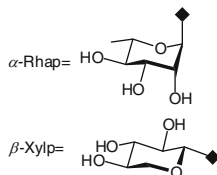
Plagiochila killarniensis was extracted with $CDCl_3$ and the crude extract analyzed by GC/MS to yield the previously known 9,10-dihydro-3,5-dimethoxyphenanthren-2-ol (1770) and 9,10-dihydro-3-methoxyphenanthren-4,5-diol (1776). These identifications were supported by means of the mass spectra of authentic samples co-injected by GC/MS (696). Compounds 1770 and 1776 were detected also in the essential oil of *Plagiochila bifaria* (277). The latter species and *P. stricta* produce 4-hydroxy-3,7-dimethoxy-9,10-dihydrophenanthrene (1777) (333, 699).

Plagiochila retrorsa elaborates 3,5-dihydroxy-4-methoxy-9,10-dihydrophenanthrene (**1778**) (**698**).

The three phenanthrenes, 9,10-dihydro-2,5,6-trimethoxyphenanthrene (**1780**), 9,10-dihydro-2,3,4,7-tetramethoxyphenanthrene (**1783**), and 9,10-dihydro-3,4,7-trimethoxyphenanthren-2-ol (**1785**), were isolated from an ether extract of the Scottish *Plagiochila spinulosa*. Methylation of **1785** gave 2,3,4,7-tetramethoxy-9,10-dihydrophenanthrene (**1783**), having spectroscopic data identical to those of the natural product **1783** (**617**). Further fractionation of the ether and methanol extracts of the British *P. spinulosa* resulted in the isolation of the same dihydrophenanthrenes, **1780**, **1783**, and **1785**, mentioned above. Among these, **1785** proved to be the major component of this specimen, with 9,10-dihydro-6-methoxyphenanthrene-2,5-diol (**1781**), 9,10-dihydro-5,6-dimethoxyphenanthren-2-ol (**1782**), and 2,3,7-trihydroxy-4-methoxy-9,10-dihydrophenanthrene (**1784**), together with the known 9,10-dihydro-3-dimethoxyphenanthren-2-ol (**1773**), 9,10-dihydro-2,3,7-trimethoxyphenanthrene (**1774**), and 9,10-dihydro-2,6-dimethoxyphenanthren-5-ol (**1775**) that were also isolated (**165**). The structures of the newly isolated compounds were proved by NOESY experiments and comparison of their spectroscopic data with those of known dihydrophenanthrenes isolated previously from liverworts (**40**). The presence of **1785** in the Belgian *P. spinulosa*, which was detected by means of GC/MS (**40**), was confirmed (**165**). The same authors substantiated the presence of 2-hydroxy-3,7-dimethoxy-9,10-dihydrophenanthrene (**1773**) by comparing with the ^1H NMR chemical shift data for the same compound isolated previously (**33**).

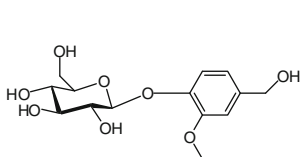
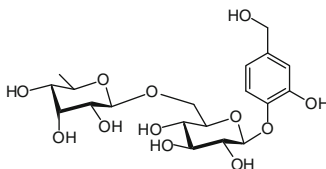
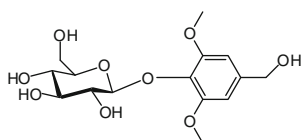
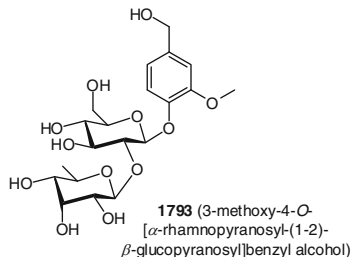
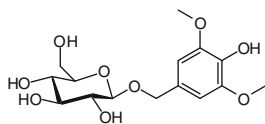
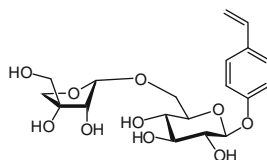
Reinvestigation of a methanol-soluble extract of *Conocephalum conicum* resulted in the isolation of a new glycoside, for which the structure was elucidated as 2-(3,4-dihydroxyphenyl)-ethyl- β -D-allopyranoside (**1786**) by a combination of spectroscopic data interpretation and by chemical reaction. Acetylation of **1786** gave a hexaacetate and its hydrolysis afforded 3,4-dihydroxyphenylethanol and D-allose. The location of the phenethyl group at C-1 β on the allose unit was confirmed by the coupling constant ($d, J = 8$ Hz) in the ^1H NMR spectrum of **1786** (**874**). This is the first example of the isolation of an allopyranosyl aromatic compound in a bryophyte.

Qu and associates (**667**) reported the isolation of four new glycosides, namely, 2,5-di-*O*- β -D-glucopyranosyl-4'-hydroxybibenzyl (**1491**), shikimic acid 4-(β -D-xylopyranoside) (**2048**), 2-(3,4-dihydroxyphenyl)ethyl-*O*- α -L-rhamnopyranosyl-(1 $\rightarrow$ 2)- β -D-allopyranoside (**1788**), and 2-(3,4-dihydroxyphenyl)ethyl-*O*- β -D-xylopyranosyl-(1 $\rightarrow$ 6)- β -D-allopyranoside (**1789**), from the water-soluble portion of the Chinese *Marchantia polymorpha*, along with three known constituents, 2-(3,4-dihydroxyphenyl)ethyl β -D-allopyranoside (**1786**) (**874**), 2-(3,4-dihydroxyphenyl)ethyl β -D-glucopyranoside (**1787**) (**641**), and 5,3',4'-trihydroxyisoflavone-7-*O*- β -D-glucopyranoside (**1921**) (**30**).

**1786** (2-(3,4-dihydroxyphenyl)-ethyl- β -D-allopyranoside)**1787** (2-(3,4-dihydroxyphenyl)-ethyl- β -D-glucopyranoside)**1788** $R^1 = \alpha$ -Rhap, $R^2 = H$ (2-(3,4-dihydroxyphenyl)-ethyl-O- α -L-rhamnopyranosyl-(1-2)- β -D-allopyranoside)**1789** $R^1 = H$, $R^2 = \beta$ -Xylp (2-(3,4-dihydroxyphenyl)-ethyl-O- β -D-xylopyranosyl-(1-6)- β -D-allopyranoside)

3,4-Dihydroxyphenethyl-O-glycosides found in the Marchantiophyta

Heteroscyphus coalitus was extracted with methanol and separated by column chromatography to give a new glycoside for which the stereostructure was deduced as 3-methoxy-4-O- β -D-glucopyranosyl-benzyl alcohol (**1790**) by analysis of its 1D- and 2D-NMR data and the formation of glucose by hydrolysis of **1790** (617).

**1790** (3-methoxy-4-O- β -D-glucopyranosyl)benzyl alcohol**1791** (4-O-[α -rhamnopyranosyl-(1-6)- β -glucopyranosyl]-3-hydroxybenzyl alcohol)**1792** (3,5-dimethoxy-4-O- β -D-glucopyranosyl)benzyl alcohol**1793** (3-methoxy-4-O-[α -rhamnopyranosyl-(1-2)- β -glucopyranosyl])benzyl alcohol)**1794** (3,5-dimethoxy-4-hydroxybenzyl-O- β -glucopyranoside)**1795** (4-O-[α -apiofuranosyl-(1-6)- β -glucopyranosyl])styrene)

Phenyl- and benzyl-O-glycosides found in the Marchantiophyta

A New Zealand specimen of *Heteroscyphus coalitus* produced 4-*O*-[α -rhamnopyranosyl-(1 $\rightarrow$ 6)- β -D-glucopyranosyl]-3-hydroxybenzyl alcohol (**1791**), together with 3-methoxy-4-*O*- β -D-glucopyranosyl-benzyl alcohol (**1790**), for which the structures were elucidated by 1D- and 2D-NMR spectroscopic (COSY and HMBC) data interpretation (617).

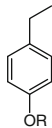
The two glucosides **1792** and **1793** were isolated from the methanol extract of the Scottish *Plagiochila spinulosa*. The spectroscopic data of **1793** were similar to those of **1792**, except for resonances for one additional methoxy group on a benzene ring. Acetylation of **1792** gave a pentaacetate with a MS fragmentation pattern suggesting the presence of glucose. The structure of **1792** was deduced as 3,5-dimethoxy-4-*O*- β -D-glucopyranosylbenzyl alcohol, via an analysis of its NOE data. A combination of the FAB-MS and ^1H and ^{13}C NMR data indicated that **1793** contains rhamnose and glucose moieties as well as a benzyl alcohol unit with one methoxy group. The spectroscopic data of the aromatic region of **1793** were very similar to those of **1792**, indicating that **1793** has a 3-methoxybenzyl alcohol unit attached to glucose and rhamnose. Acetylation of **1793** gave a heptaacetate for which the MS pattern indicated the terminal sugar to be rhamnose. That rhamnose was attached at C-2 of glucose was established by the observation of a glycosylation shift at C-2. Thus, the structure of **1793** was determined as 3-methoxy-4-*O*-[α -rhamnopyranosyl-(1 $\rightarrow$ 2)- β -D-glucopyranosyl]benzyl alcohol (617).

Plagiochila fruticosa elaborates the two aromatic glycosides **1794** and **1795**. The presence of a tetra-substituted benzyl group and β -D-glucose and the location of each functional group on the benzene ring were confirmed by a combination of 1D and 2D NMR experiments (HMBC, NOESY). The configuration at the anomeric C-atom of glucose was β since the coupling constant of H-1' was $J = 7$ Hz. Thus, the structure of **1794** was established as 3,5-dimethoxy-4-hydroxybenzyl-*O*- β -D-glucopyranoside. A *para*-substituted styrene group with an *O*- α -apiose-(1 $\rightarrow$ 6)- β -glucose in **1795** was evident from its ^1H and ^{13}C NMR data and the coupling constants $J = 7$ Hz for H-1' and $J = 2$ Hz for H-1''. Thus, the structure of **1795** was deduced as 4-*O*-[α -D-apiofuranosyl-(1 $\rightarrow$ 6)- β -D-glucopyranosyl]styrene. This is the first report of a glycoside having an ether linkage between glucose and apiose found in the liverworts (617).

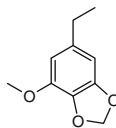
Leptolejeunea elliptica is a tiny liverwort growing on the leaves of some ferns and higher plants and emits an intensely fragrant odor when it is crushed. One of the fragrant components is 1-ethyl-4-methoxybenzene (**1797**). Further GC/MS analysis of the crude extract of this species collected in a different locality showed the presence of **1797** and two other related compounds, 1-ethyl-4-hydroxybenzene (**1796**) and 1-ethyl-4-acetoxybenzene (**1798**). These structures were proved readily by the preparation of **1797** and **1798** by methylation and acetylation of the commercially available 1-ethyl-4-hydroxybenzene (**1796**) (879).

Plagiochila rutilans is an abundant source of aromatic compounds. It produces not only the ethyl benzene derivatives **1799** and **1800**, but also 1-methoxy-4-(3-methyl-2-butenyl)benzene (**1801**), its quinone (**1803**), and the hydroquinone derivatives **1802**, **1804**, and **1805**, with the structures of the new compounds

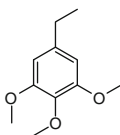
proposed using a combination of GC/MS and 2D-NMR spectroscopic data (693). The phthalide **1806**, named killarniensolide, was isolated from the CDCl_3 extract of *Plagiochila killarniensis* and its structure was determined by a combination of the mass spectrometric fragmentation pattern and by NMR spectroscopic data interpretation (696).



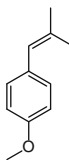
1796 R=H (1-ethyl-4-hydroxybenzene)
1797 R=Me (1-ethyl-4-methoxybenzene)
1798 R=Ac (1-ethyl-4-acetoxybenzene)



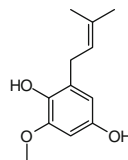
1799 (5-ethyl-1-methoxy-2,3-methylenedioxybenzene)



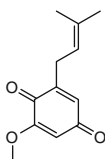
1800 (5-ethyl-1,2,3-trimethoxybenzene)



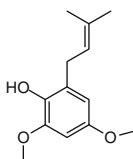
1801 (1-methoxy-4-(2-methylpropenyl)benzene)



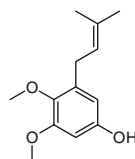
1802 (2-methoxy-6-(3-methyl-2-butenyl)-hydroquinone)



1803 (2-methoxy-6-(3-methyl-2-butenyl)-1,4-benzoquinone)



1804 (2-methoxy-4-O-methyl-6-(3-methyl-2-butenyl)-hydroquinone)



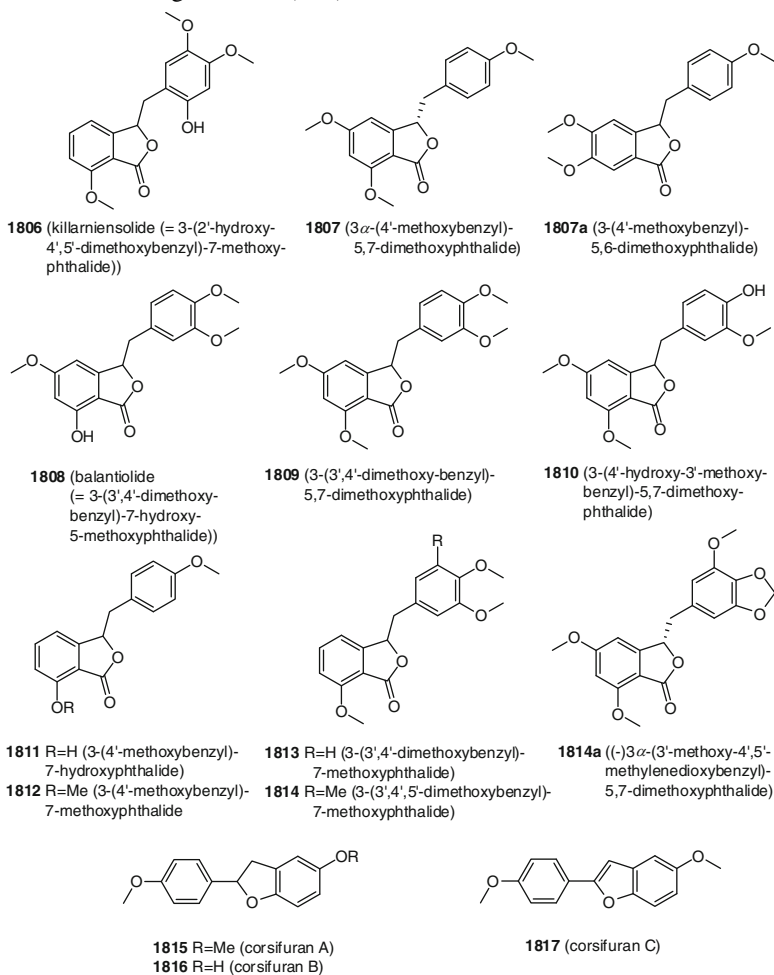
1805 (2-methoxy-1-O-methyl-6-(3-methyl-2-butenyl)-hydroquinone)

Ethyl-, 2,2-dimethylvinyl-, and 2,2-dimethylallyl-benzene derivatives found in the Marchantiophyta

Ludwiczuk and associates reported that German and Chinese collections of *Monoselenium tenerum*, belonging to the Monoseleniaceae, showed only two peaks by GC/MS and two spots on TLC (492). Preparative TLC gave the known phthalide 3 α -(4'-methoxybenzyl)-5,7-dimethoxyphthalide (**1807**), which was isolated earlier from the Australian *Frullania falciloba* (61, 78), and the new 3,5,4'-trimethoxybibenzyl (**1503**). Compound **1807** has been assigned as **1807a** (61) and then revised by Mali and coworkers to **1807** by synthesis of this ($\pm$)-3-benzylphthalide (502). The fractionation of the ether extract of an unidentified Indonesian *Frullania* species resulted in the isolation of compound **1807** and 3 α -(3'-methoxy-4',5'-methylenedioxybenzyl)-5,7-dimethoxyphthalide (**1814a**) (426), which was found earlier in *Trocholejeunea sandvicensis* (40). The presence of 3-benzylphthalides is rare in Nature. However, compound **1807** and its related bibenzyls and phthalide glycosides have been isolated from the higher plant *Tragopogon orientalis*, belonging to the family Asteraceae (985).

Fractionation of the dichloromethane extract of *Frullania muscicola* resulted in the isolation of the three dibenzyl derivatives **1808–1810** (443), of which balantiolide (**1808**) was isolated previously from the New Zealand *Balantiopsis rosea* (40). Compounds **1809** and **1810** are the methyl ether of **1808** and the demethyl derivative of **1809**, respectively. Their structures were proved to be 3-(3',4'-dimethoxybenzyl)-5,7-dimethoxyphthalide and 3-(3'-methoxy-4'-hydroxybenzyl)-5,7-dimethoxyphthalide, by comparison of their spectroscopic data with those of **1808**, and from NOE experiments.

Balantiolide (**1808**), a benzylphthalide isolated from *Balantiopsis rosea* (40), was synthesized in 66% yield by Mali and co-workers, using 5,7-dimethoxyphthalide as a starting material (501).

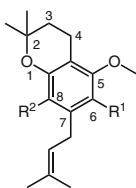


Benzylphthalides and benzofuran derivatives found in the Marchantiophyta

Three *Plagiochila* species, *P. buchitiniana*, *P. diversifolia*, and *P. longispina*, were studied chemically by the group of Heinrichs (330). 3-(4'-Methoxybenzyl)-7-hydroxyphthalide (**1811**) and its 7-methoxy derivative (**1812**) were obtained from *P. buchitiniana* and *P. diversifolia*. The latter species also produces 3-(3',4'-dimethoxybenzyl)-7-methoxyphthalalide (**1813**) and 3-(3',4',5'-trimethoxybenzyl)-7-methoxyphthalide (**1814**). Compound **1812** was also found in *P. longispina* (330).

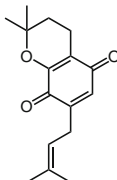
Corsifuran A (**1815**), a new 2-arylbenzofuran, was isolated from the Spanish *Corsinia coriandrina*, together with the two minor components, corsifurans B (**1816**) and C (**1817**), for which the structures were assigned tentatively from their spectroscopic data (920). The structures of corsifuran A (**1815**) was confirmed by its total synthesis by two routes: 1) the copper-catalyzed intramolecular etherification of 2-bromo-5,4'-dimethoxy-(2-hydroxybiphenyl) prepared from coupling of anisole and 2-bromo-5-methoxyphenylacetic acid, and 2) the palladium-catalyzed intermolecular etherification of the same starting material. The former method gave both a high yield and high *ee* (76% yield and 100% *ee*) and the latter a low yield and high *ee* (5% yield and 100% *ee*). On preparing both enantiomers, 2-bromo-5,4'-dimethoxy-((2*R*)-hydroxybiphenyl) and 2-bromo-5,4'-dimethoxy-2*S*-hydroxybiphenyl, followed by the etherification method mentioned above, the absolute configuration at C-8 of the natural product (**1815**) was confirmed as (*R*) (11). Cycloaddition between 4-methoxystyrene and *p*-quinone gave corsifuran B (**1816**). Methylation afforded corsifuran A (**1815**), which was dehydrogenated to afford corsifuran C (**1817**). The co-occurrence of the two stilbenoids, **1485** and **1486**, with 3,4'-dimethoxybibenzyl (**1501**) in *Corsinia coriandrina*, suggests that the 2-arylbenzofurans **1815–1817** might originate from a stilbenoid precursor (79, 920). 2-Arylbenzofuran compounds are rare in bryophytes. Only two such compounds, licarin A, from *Jackiella javanica* (40) and egonol 2-methylbutanoate (**1861**), from *Riccardia multifida* (972), are known.

Three *Metacalypogeia* and nine *Cephalozia* species occur in Japan. The ether extract of *M. cordifolia* was fractionated to afford the five new chromane derivatives **1818–1822**. Their structures were elucidated as 2,2-dimethyl-6-hydroxy-5-methoxy-7-(3-methyl-2-butenyl)-chroman (**1818**), 2,2-dimethyl-8-hydroxy-5-methoxy-7-(3-methyl-2-butenyl)-chroman (**1819**), 2,2-dimethyl-7-(3-methyl-2-butenyl)-chroman-5,8-quinone (**1820**), 2,2,2',2'-tetramethyl-5-hydroxy-dichroman (**1821**), and its methyl ether, **1822**, using a combination of chemical reactions (acetylation and methylation) and 2D-NMR (HMQC, HMBC, and NOESY) experiments (894). The same chroman (**1818**) was also isolated from the ether extract of *C. otaruensis* (894). These reports represent the first records of the isolation of chroman derivatives from the liverworts. Further study of the Taiwanese *Metacalypogeia alternifolia* led to the isolation of the isochromene, metacalypogin (**1823**), with its structure elucidated by 2D-NMR spectroscopic methods (748). *Metacalypogeia* species are chemically quite different from *Calypogeia* species, which produce mainly 1,4-dimethylazulene (**230**) and its derivatives (40).

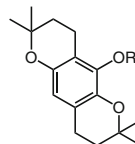


1818 R¹=OH, R²=H (6-hydroxy-5-methoxy-2,2-dimethyl-7-(3-methyl-2-butenyl)-chroman)

1819 R¹=H, R²=OH (8-hydroxy-5-methoxy-2,2-dimethyl-7-(3-methyl-2-butenyl)-chroman)

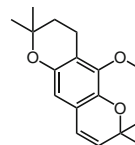


1820 (2,2-dimethyl-7-(3-methyl-2-butenyl)-chroman-5,8-dione)

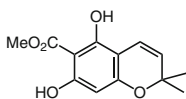


1821 R=H (5-Hydroxy-2,2,2',2'-tetramethyldichroman)

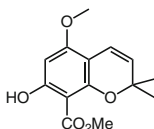
1822 R=Me (2,2,2',2'-tetramethyldichroman-5-methyl ether)



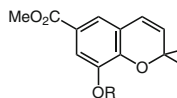
1823 (metacalypogin)



1824 (methyl 5,7-dihydroxy-2,2-dimethyl-1*H*-chromene-6-carboxylate)



1825 (methyl 7-hydroxy-5-methoxy-2,2-dimethyl-2*H*-chromene-8-carboxylate)

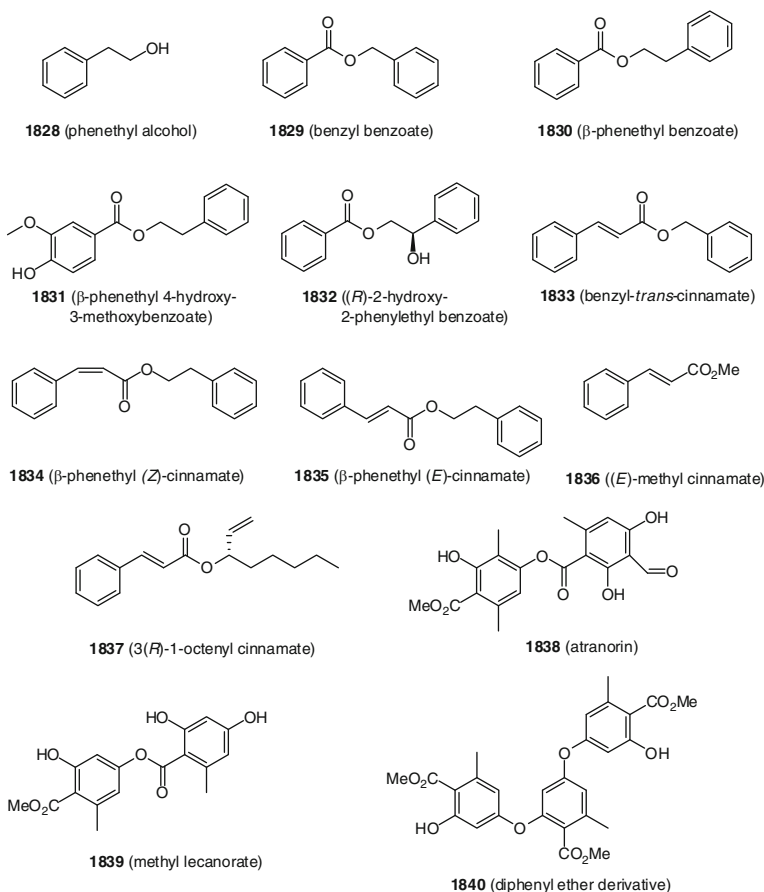


1826 R=H (methyl 8-hydroxy-2,2-dimethyl-2*H*-chromene-6-carboxylate)

1827 R=Me (methyl 8-methoxy-2,2-dimethyl-2*H*-chromene-6-carboxylate)

Chroman and chromene derivatives found in the Marchantiophyta

Fractionation of the dichloromethane extract of the Scottish *Pedinophyllum interruptum* resulted in the isolation of two new methyl chromene carboxylates, for which the structures were characterized as methyl 5,7-dihydroxy-2,2-dimethyl-2*H*-chromene-6-carboxylate (**1824**) and methyl 7-hydroxy-5-methoxy-2,2-dimethyl-2*H*-chromene-8-carboxylate (**1825**) by 2D-NMR experiments, inclusive of the NOESY spectrum measured in DMSO-*d*₆. In addition, the two similar chromenes, methyl 8-hydroxy-2,2-dimethyl-2*H*-chromene-6-carboxylate (**1826**) and methyl 8-methoxy-2,2-dimethyl-2*H*-chromene-6-carboxylate (**1827**), were obtained. It has been suggested that the chromene derivatives **1824** and **1825** might be biosynthesized from the co-occurring methyl benzoates, **1743** and **1744**, which possess a prenyl group (214).



Phenethyl alcohol, benzoate and cinnamate derivatives found in the Marchantiophyta

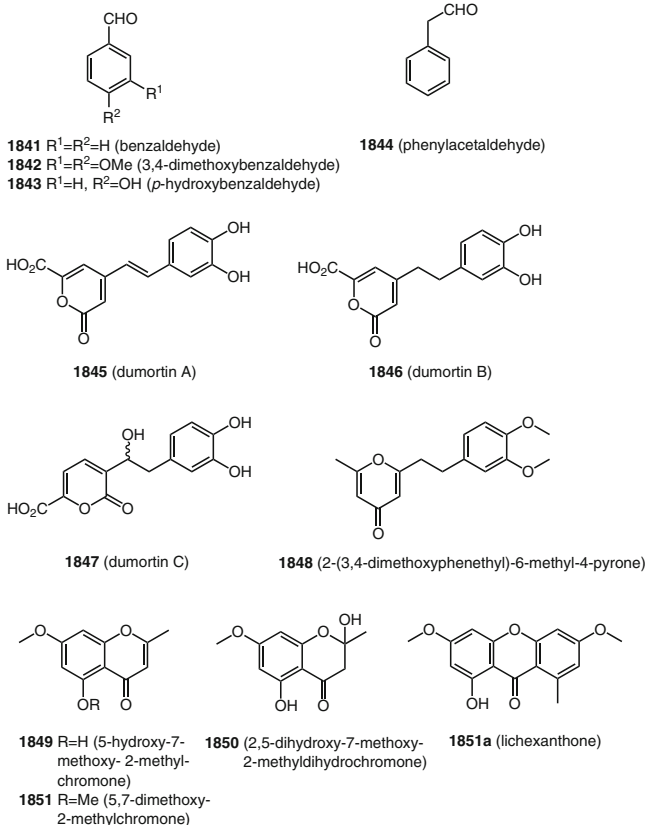
2,2-Dimethylchromenes with a 2-phenylethane unit have been isolated from the liverwort genus *Radula* (40, 178) and from *Lethocolea glossophylla* (447). *Adelanthus lindenbergianus* also produces methyl 5,7-dihydroxy-2,2-dimethyl-2*H*-chromene-6-carboxylate (1824) and methyl 7-hydroxy-5-methoxy-2,2-dimethyl-2*H*-chromene-8-carboxylate (1825) (214).

The ether extract of the New Zealand *Isotachis montana* was fractionated by column chromatography to give the new benzoate, β -phenylethyl 4-hydroxy-3-methoxybenzoate (1831), together with β -phenylethyl benzoate (1830). The nature of the functional groups of 1831 and their positions were deduced by ^1H NMR spectroscopic data analysis, and by carrying out a HMBC experiment. Some *Isotachis* species produce benzyl and β -phenylethyl *S*-methyl acrylates, as exemplified by isotachins A (1880) and B (1881). However, *I. montana* was not found to produce sulfur-containing aromatic compounds, but it elaborated the

sesquiterpene hydrocarbons, anastreptene (**122**) and (–)-*ent*-bicyclogermacrene (**293**) (**616**). A related New Zealand liverwort, *Isotachis lyallii*, produces benzyl benzoate (**1829**), β -phenylethyl (*Z*)-cinnamate (**1834**), and β -phenylethyl (*E*)-cinnamate (**1835**). Two unidentified Peruvian *Isotachis* species were also found to produce benzyl benzoate (**1829**), β -phenylethyl benzoate (**1830**), and benzyl (*E*)-cinnamate (**1833**) as well as the thioacrylates isotachin A (= benzyl (*E*)- β -methylthioacrylate) (**1880**) and isotachin B (= β -phenylethyl (*E*)- β -methylthioacrylate) (**1881**) (see later in this section) (**73**), which have been found previously in the Japanese *Isotachis japonica* (**40**). The ether extract of the Madagascan *Isotachis aubertii* contained β -phenethyl benzoate (**1830**), β -phenethyl (*E*)-cinnamate (**1835**), and isotachins A (**1880**) and B (**1881**), together with gymnomitr-3(15)-en-5 α -ol (**246**) and palmitic acid. GC/MS analysis of the extract also confirmed that *I. aubertii* produces phenethyl alcohol (**1828**) and β -phenethyl (*Z*)-cinnamate (**1834**), along with several known sesquiterpenoids, and methyl palmitate (**288**). *I. lyallii* and an unidentified Peruvian *Isotachis* species both elaborate benzyl benzoate (**1829**), with the former species producing also β -phenylethyl (*Z*)-cinnamate (**1834**), β -phenylethyl (*E*)-cinnamate (**1835**), and benzyl benzoate (**1829**). *I. montana* and an unidentified Peruvian *Isotachis* species were found to contain β -phenylethyl benzoate (**1830**) (**73**, **616**).

The Chilean *Balantiopsis erinacea* contains 2-phenylethanol in the form of the esters **1830** and **1833** (**40**). A study on the chemical constituents of the dichloromethane extract of *Balantiopsis cancellata* led to the isolation of the four known 2-phenylethanol esters **1830**, **1834**, **1835**, and **1881**, together with 2-hydroxy-2-phenylethyl benzoate (**1832**), for which the absolute configuration was suggested as (*R*), from its negative optical rotation value (**457**). This was the first isolation of **1832** from a liverwort. Compounds **1830**, **1834**, **1835**, and **1881** have been found in *Balantiopsis rosea* and *Isotachis japonica* (**40**).

Wood and associates reported the presence of methyl cinnamate (**1836**) in the American *Conocephalum conicum* as the major component (**945**). The same component was found earlier in one of the chemotypes of the Japanese *C. conicum* (**880**). 1-Octen-3(*R*)-yl cinnamate (**1837**) was isolated from the ether extract of *Isotachis lyallii* collected in New Zealand. This is the first cinnamic acid ester with matsutakeol (= 1-octen-3-ol) to have been reported in the plant kingdom (**84**). Atranorin (**1838**), which has been isolated from a lichen species (**359**), was found in *Trocholejeunea sandvicensis* (**460**) and an unidentified Indonesian *Frullania* species (**426**). 3,4-Dimethoxybenzaldehyde (**1842**) and 4-hydroxybenzaldehyde (**1843**) were isolated from the ether extract of an unidentified Japanese *Asterella* species and *Marchantia tosaana* (**71**, **459**).

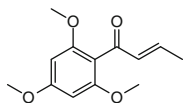


Benzaldehyde and its derivatives, and phenylacetaldehyde, α - and γ -pyrones, and xanthone derivatives found in the Marchantiophyta

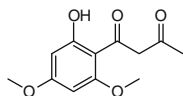
The additional fractionation of a methanol extract of *Dumortiera hirsuta* resulted in the isolation of the three carboxylated α -pyrones, dumortins A-C (**1845–1847**), with their structures elucidated as 4-(3',4'-dihydroxy-(*E*)-styryl)-6-carboxy- α -pyrone, 4-[2-(3',4'-dihydroxyphenyl)-ethyl]-6-carboxy- α -pyrone, and 3-[1-hydroxy-2-(3',4'-dihydroxyphenyl)-ethyl]-6-carboxy- α -pyrone using a combination of UV/Vis, FAB-MS, and 1D- and 2D-NMR (DEPT, HMQC, HMBC, and NOE) experiments. Conclusive evidence for the structures of **1845** and **1846** was based on their total synthesis by an olefination reaction. Wittig reaction between veratraldehyde and methyl 4-(methyltriposponium bromide)-2-oxo-2*H*-pyran-6-carboxylate yielded (*E*)- and (*Z*)-styrylpyrones. Demethylation of the latter followed by saponification gave dumortin A (**1845**) in 72% yield, while demethylation and hydrogenation of (*E*)-styrylpyrone furnished dumortin B (**1846**) in 75% yield (445). Such pyrones with substitution at C-3 are known in some liverworts (40, 556, 809), but an α -pyrone with a substituent at C-4 is so far unknown in the plant kingdom.

The New Zealand *Hymenophyton flabellatum* belonging to the Hymenophytaceae shows intense pungency when chewed. Column chromatography of

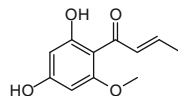
the ether extract afforded the pungent-tasting 1-(2,4,6-trimethoxyphenyl)-but-(2*E*)-en-1-one (**1852**), in addition to 1-(2-hydroxy-4,6-trimethoxyphenyl)-but-1,3-dione (**1853**). The structure of **1852** was established by 2D-NMR data analysis and by its synthesis. The reaction of 1,3,5-trimethoxybenzene with crotonyl chloride using aluminum chloride as the catalyst gave **1852** (**900**). It is noteworthy that the same compound **1852** has been isolated from the Japanese fern, *Arachinoides standishii* (**803**) as well as the higher plant, *Dysophylla verticillata* (Labiatae) (**150**).



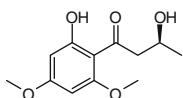
1852 (1-(2,4,6-trimethoxyphenyl)-but-(2*E*)-en-1-one)



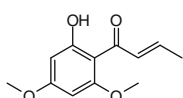
1853 (1-(2-hydroxy-4,6-dimethoxyphenyl)-butan-1,3-dione)



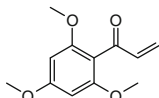
1854 (1-(2,4-dihydroxy-6-methoxyphenyl)-but-(2*E*)-en-1-one)



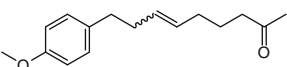
1855 (1-(2-hydroxy-4,6-dimethoxyphenyl)-(3*R*)-hydroxy-1-butanone)



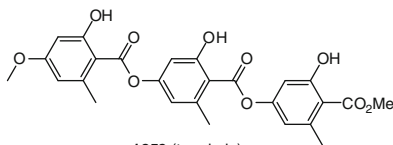
1856 (1-(2-hydroxy-4,6-trimethoxyphenyl)-but-(2*E*)-en-1-one)



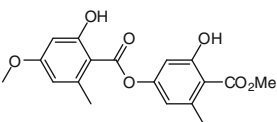
1857 (1-(2,4,6-trimethoxyphenyl)-but-(2*Z*)-en-1-one)



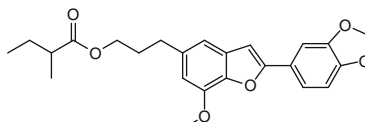
1858 (9-(4-methoxyphenyl)-6-nonen-2-one)



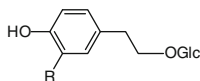
1859 (tenuiorin)



1860 (methyl evermate)



1861 (egonol-2-methylbutanoate)



1862 R=H (salidroside)

1863 R=OH (β -(3,4-dihydroxyphenyl)ethyl-*O*- β -D-glucoside)

Phenylbutanone and the other aromatic compounds found in the Marchantiophyta

Further fractionation of the same extract of *H. flabellatum* led to the isolation of the three chromones, **1849–1851**, and the four phenylbutan-1-one derivatives, **1854–1857** (**84**, **900**). 5-Hydroxy-7-methoxy-2-methylchromone (**1849**) and 5,7-dimethoxy-2-methylchromone (**1851**), which are dehydro derivatives of **1850**, have

been found in *Baeckea frutescens* (905) and *Scutellaria baicalensis* (552), respectively. The presence of a hemiketal functionality in the new dihydrochromone derivative **1850** was proposed on the basis on the ^{13}C NMR chemical shift observed at δ_{C} 100.7 ppm. Its gross structure was assigned as 2,5-dihydroxy-7-methoxy-2-methylidihydrochromone, by comparison of spectroscopic data with those of **1849** and **1851** and analysis of its 2D-NMR parameters. The presence of (*E*)-2-buten-1-one and a hydrogen-bonded OH group (δ_{H} 14.11 ppm) in **1854** was evident from the ^1H and ^{13}C NMR data. Functional group orientation in **1854** was confirmed by means of a NOESY experiment (900). Since **1855** isolated from *H. flabellatum* was optically active, the absolute configuration of the secondary hydroxy group was studied by anomalous X-ray crystallographic analysis of 1-(3,5-dibromo-2-hydroxy-4,6-dimethoxy-phenyl)-3(*R*)-hydroxy-1-butanone, thereby establishing that **1855** is 1-(2-hydroxy-4,6-dimethoxyphenyl)-3(*R*)-hydroxy-1-butanone. A glycoside of **1855** has been found not only in the ferns *Arachinoides standishii* (803) and *Diplazium nipponicum* (346) and **1855** has also been reported as a synthetic intermediate of **1852** and **1856** (95). However, this is the first isolation of **1855** as a natural product. The aglycone **1855** derived from a fern *Diplazium nipponicum* constituent has been established as (*S*)-configured by the modified Horeau method (346). Thus, the liverwort *H. flabellatum* and the fern *D. nipponicum* produce both enantiomers of **1855**. The occurrence of this phenylbutenone in both liverworts and pteridophytes provides an evolutionary link between bryophytes and pteridophytes (see Chap. 9). The structure of **1857** was deduced by comparison of ^1H and ^{13}NMR spectroscopic data with those of **1852**. The chemical shift at δ_{H} 6.34 and 6.21 ppm (each $J = 11.5$ Hz) showed the presence of a (*Z*)- α,β -unsaturated ketone in **1857** (900). Lichexanthone (**1851a**), which has been obtained from the lichen species, *Hypotrachyna formosana* and *Lecidella stigmataea* (359), was isolated from an unidentified Indonesian *Frullania* species (426).

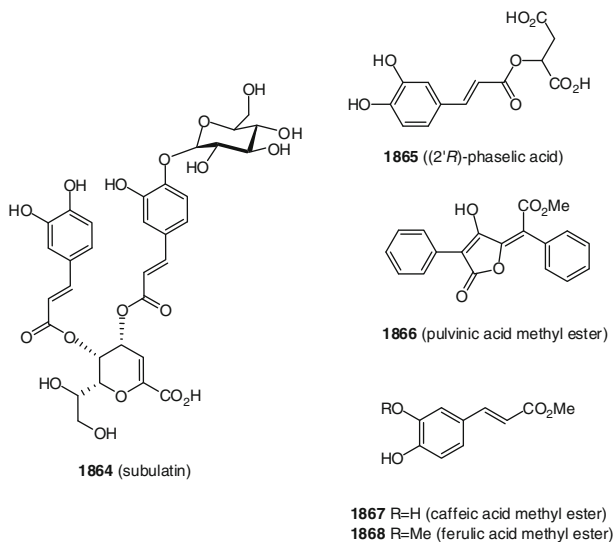
Yoshida and colleagues reported the isolation from *Blasia pusilla* not only of bis-bibenzyl dimers and monomers but also the lichen depsides tenuiorin (**1859**) and methyl evernate (**1860**) (971). The methanol extract of *Frullania nisqualensis* gave the same compound **1859** (410). An ether extract of the Japanese *Bazzania tricenata* also produces **1859**, along with the widely occurring sesquiterpenoids bicyclogermacrene (**296**), 5-hydroxy- (**406**) and 7-hydroxycalamenene (**408**), 2-cuparenol (**483**), and drimenol (**538**). This is the first isolation of the lichen constituents from the Lepidoziaceae (84). Further fractionation of the methanol extract of *Riccardia multifida* subsp. *decrescens* led to the isolation of egonol 2-methylbutanoate (**1861**) (972), which has been found also in the higher plant, *Styrax obassia* (Styracaceae) (799).

The fractionation of a methanol extract of *Marchantia polymorpha* gave the two known phenolic glucosides, salidoroside (**1862**) and β -(3,4-dihydroxyphenyl)-*O*- β -D-glucopyranoside (**1863**) (634), which have been isolated from *in vitro* cultures of *Ricciocarpos natans* (Ricciaceae) (40, 452). The latter compound has also been purified from the *n*-butanol extract of sterile *in vitro* cultures of the German *M. polymorpha* (8).

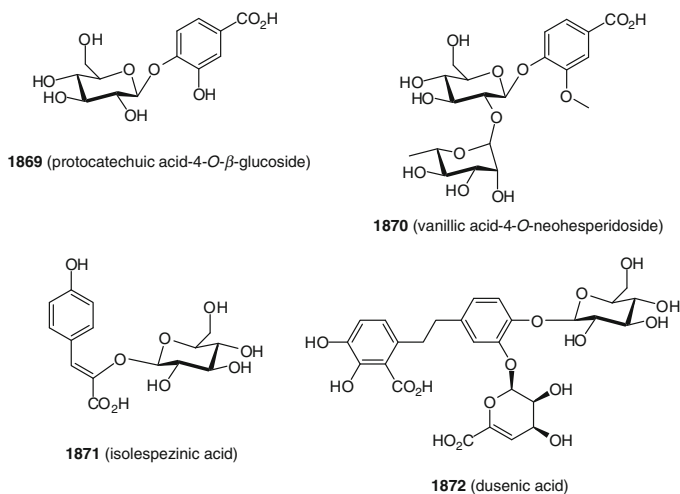
Subulatin (**1864**), a new caffeic acid derivative, was isolated from a methanol extract of the *in vitro*-cultured *Jungermannia subulata* together with (2'*R*)-phaseelic acid (**1865**), using HPLC with separation on an ODS column. Similar separations performed on the crude extracts of *Lophocolea heterophylla* and *Scapania parvixesta* afforded **1864** (**823**). The stereostructure of **1864** was deduced by a combination of a chemical reaction, which confirmed the presence of the β -D-glucose moiety, FAB mass spectrometry, as well as extensive NMR analysis, including HSQC, COSY, TOCSY, HSQC, ROESY, and HMBC experiments. The absolute configurations at C-4 and C-5 were assigned as (4*R*,5*R*) from the negative (287 nm) and positive (339 nm) Cotton effects observed. Similar lignans have been isolated from *Bazzania trilobata* (**523**) and *Lepicolea ochroleuca* (**177**). Compound **1865** was isolated from the higher plant, *Chelidonium majus* (**283**). However, the optical rotation of **1865** from higher plant, *C. majus* is opposite to that of the same compound obtained from liverwort, *J. subulata*. As mentioned earlier, *Lophocolea heterophylla* biosynthesizes (–)-epiphylllic acid (**1690**) and 9,2''-epiphyllloyl malic acid (**1691**). To compare with the authentic compounds **1865** and **1691** isolated from *Jungermannia subulata* and *L. heterophylla*, (*E*)-caffeoyl-L-malic acid was obtained from *Trifolium subterraneum* (**925**). To determine the configuration of malic acid in compounds **1865** and **1691**, both compounds were esterified with diazomethane, and were then, after alkaline hydrolysis, 4-bromobenzoylated to afford the 4-bromobenzoyl malic acid dimethyl esters. These were analyzed by means of enantio-differentiating HPLC to confirm that **1865** is (*E*)-caffeoyl-D-malic acid and **1691** is (–)-9,2''-epiphyllloyl-L-malic acid. It is noteworthy that the configuration of malic acid in compound **1865** is (+)-D-malic acid (91.2% *ee*) and that of malic acid in **1691** is (–)-L-malic acid (100% *ee*) (**823**)).

The New Zealand *Tylimanthus tenellus* produces not only humulane sesquiterpenoids esterified with puluvinic acid but also puluvinic acid methyl ester (**1866**), which has been found in many lichens (**359**). The structure of **1866** was confirmed by X-ray crystallographic analysis (**896**). This was the first report of the isolation of compound **1866** from the liverworts. The ether extract of the sporophytes of *Pellia epiphylla* was purified by column chromatography to give caffeic acid methyl ester (**1867**) and ferulic acid methyl ester (**1868**), which were determined to be artifacts obtained during extraction by methanol (**175**).

The *n*-butanol-soluble part of the methanol extract of *Lepicolea ochroleuca* was purified to give protocatechuic acid-4-*O*- β -D-glucose (**1869**) (**177**), which has been found in the fern *Angiopraxis lygodifolia* (**559**) and the higher plant *Picea glauca* (**440**). Final proof of the structure of **1869** was carried out by the analysis of HMBC and NOESY experiments. The polar compound **1870** from the aqueous methanol extract of *Chandonanthus hirtellus* subsp. *giganteus* was analyzed by a combination of FAB-MS and ¹H- and 2D-NMR (COSY and NOESY) methods, and determined structurally as vanillic acid-4-*O*-neohesperidoside (**441**).



Cinnamic acid derivatives found in the Marchantiophyta



Benzoic and cinnamic acid derivatives found in the Marchantiophyta

The methanol extract of *Plagiochila duseii* was purified by column chromatography to afford the new benzyl glucoside, dusenec acid (**1872**) (32), together with the known isolespezinic acid (**1871**) (740), and an unknown lignan derivative. Two benzylic methylene signals, five aromatic resonances with a spin pattern consistent with two *ortho*- protons, and an ABM spin system were proposed from the ^1H NMR spectrum of **1872**. In addition, *O*- β -D-glucopyranoside and *O*-(4-deoxy- α -L-erythro-hex-4-ene-pyranosyl)uronic acid units in this molecule were evident from ^{13}C NMR, COSY and NOESY NMR spectroscopic experiments, and as a result of hydrolysis

of **1872**. The substitution pattern and the locations of the attachment of the glucose and deoxyuroic acid moieties were confirmed for compound **1872** by NOESY and HMQC correlations.

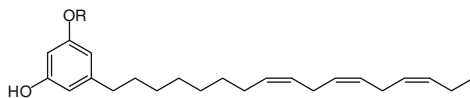
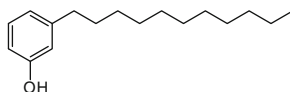
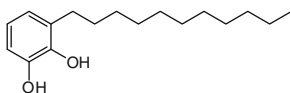
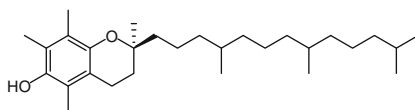
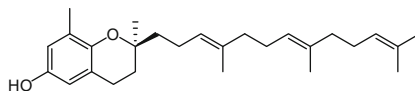
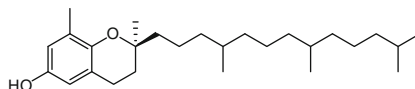
The isolation and preliminary structural assignment of compound **1873** as 5-heptadeca-(8Z,11Z,14Z)-trienylresorcinol monomethyl ether, from the Colombian liverwort, *Omphalanthus filiformis*, have been reported (40). Further structural proof for **1873** using COSY, TOCSY, HMBC, and NOESY NMR correlations has been published (844).

Schistochila appendiculatum is chemically quite distinct from the other Marchantiophyta species, since it elaborates high concentration levels of alkyl phenols (40). Previously, the presence of 6-undecylcatechol (**1875**) was shown for this species (40). Further fractionation of the ether extract of *S. appendiculata* resulted in the isolation of 3-undecylphenol (**1874**) (72, 616).

Several liverworts contain small amounts of tocopherols. α -Tocopherol (**1876**) was isolated from both an Arctic specimen of *Fossombronia alaskana* (268) and the ether extract of the New Zealand *Plagiochila circinalis* (635). Among 726 liverworts collected worldwide, 266 species (36.3%) were shown to accumulate α -tocopherol. In particular, 65% of *Porella* and *Pellia* species containing pungent sesqui- or diterpene dialdehydes elaborated α -tocopherol (**1876**). Moreover, pungent medicinal plants such as *Polygonum hydropiper* (Polygonaceae), *Cinnamosma fragrans*, and *C. macrocarpa* (Cannellaceae) produce α -tocopherol (**1876**) and δ -tocotrienol (**1876a**) (297). These tocopherols may play an important role as antioxidants for not only sesqui- and diterpene dialdehydes, but also for other higher unsaturated terpenoids and lipids found in liverworts (82).

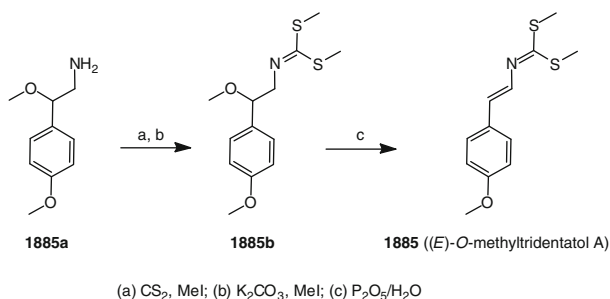
Ether extracts of the European *Pellia epiphylla* (176), the Japanese *Jungermannia infusca* (597), and the New Zealand *Radula marginata* (895) and *Marchantia berteroana* (616) were purified by column chromatography and HPLC to yield δ -tocopherol (**1877**), which has been isolated from the liverwort *Radula perrottetii* (40). Bioactivity-guided fractionation of the ether extract of *Plagiochila ovalifolia* using the DPPH-radical scavenging assay resulted in the isolation of δ -tocopherol (**1877**), which exhibited antioxidative activity in the test system used (30–85% inhibition at 50–200 μ g) (701). *Lepidozia spinosissima* also produces (+)- δ -tocopherol (**1877**) (72, 616).

A Malaysian liverwort identified as *Asterella* or *Mannia* species produces a very strong unpleasant fecal smell. GC/MS analysis of the ether extract indicated the presence of 1-octen-3-ol (**1940**) (1%) and skatole (**1878**) (23%), which is a well-known compound produced by biodegradation of tryptophan and produces a fecal odor (72). This is the first identification of **1878** among the bryophytes. *Ludwiczuk* and associates reported that the Tahitian *Cyathodium foetidissimum* exhibits a very strong unpleasant odor when it is crushed. GC/MS analysis of the ether extract indicated the presence of **1878** as a minor component (494). 3-Indole acetic acid (**1879**) was detected in the gametophyte of *Marchantia polymorpha* (467).

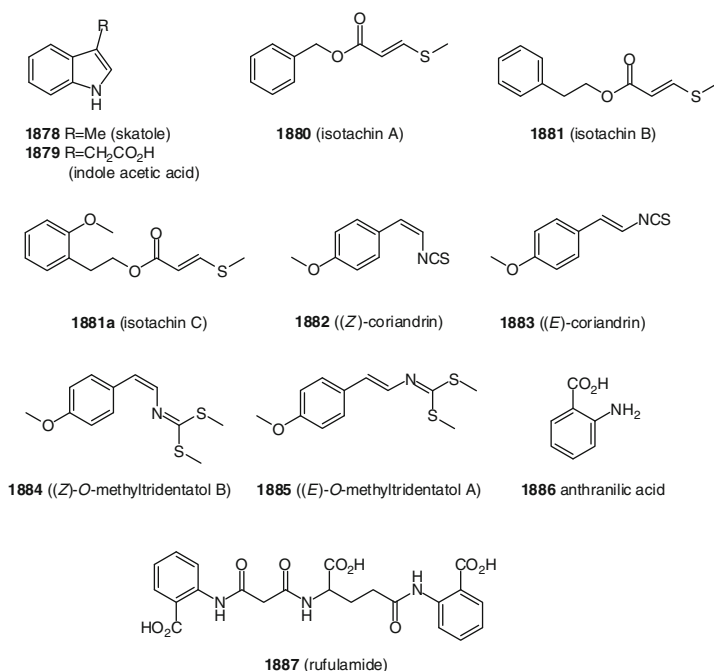
**1873** R=Me (5-heptadeca-(8Z,11Z,14Z)-trienylresorcinol monomethyl ether)**1873a** R=H**1874** (3-undecylphenol)**1875** (1,2-dihydroxy-6-undecylbenzene (= 6-undecylcatechol))**1876** (α -tocopherol)**1876a** (δ -tocotrienol)**1877** (δ -tocopherol)

Alkylphenols and tocopherols found in the Marchantiophyta

Corsinia coriandrina is a thalloid liverwort that grows in the Mediterranean region. When crushed by hand, it emits a sulfur-like smell. *von Reuß* and *König* isolated four unique sulfur-nitrogen-containing compounds in the coriandrin and *O*-methyltridentatol series and their structures were established as (Z)- (**1882**) and (*E*)-2(4-methoxyphenyl)ethenyl isothiocyanate (**1883**), and (Z)- (**1884**) and (*E*)-*S,S*-dimethyl-2-(4-methoxyphenyl)ethenyliminodithiocarbonate (**1885**) by means of 2D-NMR analysis ([921](#)). The total synthesis of **1885** was carried out as shown in Scheme [4.55](#) ([376](#)). This was the first report of the isolation of isothiocyanates and iminothiocarbonates from the Marchantiophyta. Free phenols and *O*-sulfates corresponding to **1884** and **1885** have been isolated from the marine hybrid, *Tridentata marginata* (Sertulariidae), and named as tridentatols ([471](#), [472](#)).



Scheme 4.55 Total synthesis of (*E*)-*O*-methyltridentatol A



Sulfur-, nitrogen-, and sulfur/nitrogen-containing aromatic compounds found in the Marchantiophyta

Metzgeria species are very small and thin liverworts, and produce mainly flavone C-glycosides (40). An aqueous methanol extract of *Metzgeria rufula* was shown to contain rufulamide (1887), an oligopeptide analogue consisting of L-glutamic acid, malonic acid, and two molecules of anthranilic acid (1886) combined *via* amide bonds (446). Conclusive evidence of the structure of 1887 was confirmed by 2D-NMR experiments and its total synthesis by a straightforward convergent strategy from the building blocks 2-(2-carboxyacetyl)-benzyl benzoate and 2-(4-amino-4-benzyloxycarbonyl-butrylamino)-benzylbenzoate-trifluoroacetate using DCC and *N*-hydroxybenzotriazole as coupling reagents. The free anthranilic acid (1886) was also been detected in this liverwort.

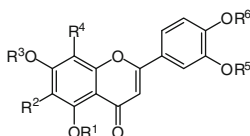
Fractionation of a methanol extract of the Japanese *Marchantia polymorpha* gave adenosine (634), which has also been isolated from the *n*-butanol extract of sterile cultures of the German *M. polymorpha* with tryptophan (8).

Suspension cultured cells of *Marchantia polymorpha* showed very high enantioselectivities in the hydrolysis of racemic 1,2- and 1,3-diacetoxycyclohexanes and their related compounds at the stereogenic center with (*R*)-configuration. Asymmetry was also induced in the hydrolyses of *meso*-1,2- and 1,3-diacetates to the corresponding monoacetates (343).

4.6 Flavonoids

4.6.1 Flavones and Flavanones

Flavonoids are ubiquitous minor components in the Marchantiophyta. All of the three orders, Jungermanniales, Metzgeriales, and Marchantiales contain flavonoids. Flavones are more common than flavanones in bryophytes (40). Luteolin (1888), apigenin (1910) and their derivatives are most abundant in the Marchantiophyta, as shown in Table 4.8.



- 1888 $R^1=R^2=R^3=R^4=R^5=R^6=H$ (luteolin)
 1889 $R^1=R^2=R^4=R^5=R^6=H$, $R^3=Me$ (luteolin-7-methyl ether)
 1890 $R^1=R^2=R^4=R^6=H$, $R^3=R^5=Me$ (luteolin-7,3'-dimethyl ether (= vetulin))
 1891 $R^1=R^2=R^3=R^4=H$, $R^5=R^6=Me$ (luteolin-3',4'-dimethyl ether)
 1892 $R^1=R^2=R^4=H$, $R^3=R^5=R^6=Me$ (luteolin-7,3',4'-trimethyl ether)
 1893 $R^2=R^3=R^6=H$, $R^1=R^3=R^5=Me$ (luteolin-5,7,4'-trimethyl ether)
 1894 $R^2=R^3=R^4=R^5=R^6=H$, $R^1=GlcA$ (luteolin-5-*O*-glucuronide)
 1895 $R^1=R^2=R^4=R^5=R^6=H$, $R^3=GlcA$ (luteolin-7-*O*-glucuronide)
 1895a $R^1=R^2=R^4=R^5=H$, $R^3=R^6=GlcA$ (luteolin-7,4'-di-*O*-glucuronide)
 1896 $R^2=R^3=R^4=R^5=R^6=H$, $R^1=GlcA$ -6-methyl ester (luteolin-5-*O*-glucuronide-6"-methyl ester)
 1897 $R^1=R^2=R^3=R^4=R^6=H$, $R^5=GlcA$ (luteolin-3'-*O*- β -*D*-glucuronide)
 1898 $R^1=R^2=R^4=R^6=H$, $R^3=R^5=GlcA$ (luteolin-7,3'-di-*O*- β -*D*-glucuronide)
 1899 $R^1=R^2=R^4=R^5=R^6=H$, $R^3=Glc$ (luteolin-7-*O*-glucoside)
 1900 $R^1=R^2=R^4=R^5=R^6=H$, $R^3=Neohesp$ (luteolin-7-*O*-neohesperidoside)
 1901 $R^1=R^4=R^5=R^6=H$, $R^2=O-Glc$, $R^3=Glc$ (6-OH-luteolin-6-*O*-glucoside-7-*O*-glucoside)
 1902 $R^1=R^4=R^5=R^6=H$, $R^2=O-Glc$, $R^3=Glc$ -6-HMG (6-OH-luteolin-6-*O*- β -*D*-glucoside-7-*O*- β -*D*-glucoside-6"-[(3-hydroxy-3-methylglutaryl ester)])
 1903 $R^1=R^3=R^5=R^6=H$, $R^2=R^4=Glc$ (luteolin-6,8-di-*C*- β -*D*-glucoside(=lucenin 2))
 1904 $R^1=R^4=R^6=H$, $R^2=OH$, $R^3=Glc$ -6-HMG, $R^5=GlcA$ (6-OH-luteolin-7-*O*- β -*D*-glucoside-6"-[(3-hydroxy-3-methylglutaryl ester)-3'-*O*-glucuronide])
 1905 $R^1=R^4=R^5=H$, $R^2=OMe$, $R^3=2-O-\alpha$ -Rha-3-*O*- α -Ara- β -GlcA, $R^6=2-O-\alpha$ -Rha-3-*O*- β -Xyl- β -GlcA (6-methoxyluteolin 7-*O*-[2-*O*- α -rhamnosyl-3-*O*- α -arabinosyl- β -glucuronide]-4'-*O*-[2-*O*- α -rhamnosyl-3-*O*- β -xylosyl- β -glucuronide])
 1906 $R^1=R^4=R^5=H$, $R^2=OMe$, $R^3=2-O-\alpha$ -Rha- β -GlcA, $R^6=2-O-\alpha$ -Rha-3-*O*- β -Xyl- β -GlcA (6-methoxyluteolin 7-*O*-[2-*O*- α -rhamnosyl- β -glucuronide]-4'-*O*-[2-*O*- α -rhamnosyl-3-*O*- β -xylosyl- β -glucuronide])
 1907 $R^1=R^4=R^5=H$, $R^3=2-O-\alpha$ -Rha-3-*O*- α -Ara- β -GlcA, $R^6=2-O-\alpha$ -Rha-3-*O*- β -Xyl- β -GlcA (luteolin 7-*O*-[2-*O*- α -rhamnosyl-3-*O*- α -arabinosyl- β -glucuronide]-4'-*O*-[2-*O*- α -rhamnosyl-3-*O*- β -xylosyl- β -glucuronide])
 1908 $R^1=R^2=R^4=R^5=H$, $R^3=2-O-\alpha$ -Rha- β -GlcA, $R^6=2-O-\alpha$ -Rha-3-*O*- β -Xyl- β -GlcA (luteolin 7-*O*-[2-*O*- α -rhamnosyl- β -glucuronide]-4'-*O*-[2-*O*- α -rhamnosyl-3-*O*- β -xylosyl- β -glucuronide])

Flavonoids found in the Marchantiophyta

Table 4.8 Flavonoids and anthocyanidins found in the Marchantiophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1888	Luteolin	$\text{C}_{15}\text{H}_{10}\text{O}_6$			<i>Chandonanthus hirtellus</i> subsp. <i>giganteus</i>	(441)	
					<i>Dumortiera hirsuta</i>	(445)	
					<i>Marchantia palmata</i>	(8)	Cell culture
						(193)	
1889	Luteolin-7-methyl ether	$\text{C}_{16}\text{H}_{12}\text{O}_6$			<i>Pellia epiphylla</i>	(175)	Sporophyte
1890	Luteolin-7,3'-dimethyl ether (=Vetulin)	$\text{C}_{17}\text{H}_{14}\text{O}_6$			<i>Pellia epiphylla</i>	(175)	Sporophyte
					<i>Frullania teneriffae</i>	(444)	
					<i>Pellia epiphylla</i>	(175)	Sporophyte
1891	Luteolin-3',4'-dimethyl ether	$\text{C}_{17}\text{H}_{14}\text{O}_6$			<i>Plagiochila diversifolia</i>	(330)	
1892	Luteolin-7,3',4'-trimethyl ether	$\text{C}_{18}\text{H}_{16}\text{O}_6$			<i>Frullania teneriffae</i>	(444)	
					<i>Frullania teneriffae</i>	(444)	
					<i>Plagiochila diversifolia</i>	(330)	
1893	Luteolin-5,7,3'-methyl ether	$\text{C}_{18}\text{H}_{16}\text{O}_6$			<i>Pellia epiphylla</i>	(175)	Sporophyte
1894	Luteolin-5-O-glucuronide	$\text{C}_{21}\text{H}_{18}\text{O}_{12}$			<i>Dumortiera hirsuta</i>	(445)	
1895	Luteolin-7-O-glucuronide	$\text{C}_{21}\text{H}_{18}\text{O}_{12}$			<i>Dumortiera hirsuta</i>	(445)	
1896	Luteolin-5-O-glucuronide-6''-methyl ester	$\text{C}_{22}\text{H}_{20}\text{O}_{12}$			<i>Dumortiera hirsuta</i>	(445)	
1897	Luteolin-3'-O-β-D-glucuronide	$\text{C}_{21}\text{H}_{18}\text{O}_{12}$			<i>Marchantia palmata</i>	(193)	
1898	Luteolin-7,3'-di-O-β-D-glucuronide	$\text{C}_{27}\text{H}_{26}\text{O}_{18}$			<i>Marchantia palmata</i>	(193)	
1899	Luteolin-7-O-glucoside	$\text{C}_{21}\text{H}_{20}\text{O}_{11}$			<i>Lunularia cruciata</i>	(371)	
1900	Luteolin-7-O-neohesperidoside	$\text{C}_{27}\text{H}_{30}\text{O}_{15}$			<i>Frullania teneriffae</i>	(444)	
1901	6-Hydroxyluteolin-6-O-glucosyl-7-O-glucoside	$\text{C}_{27}\text{H}_{30}\text{O}_{18}$			<i>Frullania teneriffae</i>	(444)	
1902	6-Hydroxyluteolin-6-O-β-D-glucosyl-7-O-β-D-glucosyl-6''-(3-hydroxy-3-methyl)glutaroyl ester	$\text{C}_{33}\text{H}_{38}\text{O}_{22}$			<i>Frullania teneriffae</i>	(444)	
1903	Luteolin-6,8-di-C-β-D-glucoside (=Lucenin 2)	$\text{C}_{27}\text{H}_{30}\text{O}_{16}$			<i>Frullania cesatiana</i>	(444)	

1904	6-Hydroxyluteolin-7- <i>O</i> - β - <i>D</i> -glucosyl-6''-(3-hydroxy-3-methylglutaroyl ester)-3'- <i>O</i> -glucuronide	C ₃₃ H ₃₆ O ₂₂	<i>Frullania arecae</i> (444)
1905	MF-1a [6-Methoxyluteolin 7- <i>O</i> -[2- <i>O</i> - α -rhamnosyl-3- <i>O</i> - α -arabinosyl- β -glucuronide]-4'- <i>O</i> -[2- <i>O</i> - α -rhamnosyl-3- <i>O</i> - β -xylosyl- β -glucuronide]]	C ₅₀ H ₆₂ O ₃₅	<i>Frullania cesatiana</i> (444)
1906	MF-1b [6-Methoxyluteolin 7- <i>O</i> -[2- <i>O</i> - α -rhamnosyl- β -glucuronide]-4'- <i>O</i> -[2- <i>O</i> - α -rhamnosyl-3- <i>O</i> - β -xylosyl- β -glucuronide]]	C ₄₅ H ₅₄ O ₃₁	<i>Frullania gibbosa</i> (510)
1907	MF-1a' [Luteolin 7- <i>O</i> -[2- <i>O</i> - α -rhamnosyl-3- <i>O</i> - α -arabinosyl- β -glucuronide]-4'- <i>O</i> -[2- <i>O</i> - α -rhamnosyl-3- <i>O</i> - β -xylosyl- β -glucuronide]]	C ₄₉ H ₆₀ O ₃₄	<i>Monoclea forsteri</i> (510)
1908	MF-1b' [Luteolin 7- <i>O</i> -[2- <i>O</i> - α -rhamnosyl- β -glucuronide]-4'- <i>O</i> -[2- <i>O</i> - α -rhamnosyl-3- <i>O</i> - β -xylosyl- β -glucuronide]]	C ₄₄ H ₅₂ O ₃₀	<i>Monoclea forsteri</i> (510)
1909	Dicranolomin (=2',6''-Bisluteolin)	C ₃₀ H ₁₈ O ₁₂	<i>Chandonanthus hirtellus</i> subsp. <i>giganteus</i> (441)
1910	Apigenin	C ₁₅ H ₁₀ O ₅	<i>Marchantia palmata</i> (193)
1911	Apigenin-7-methyl ether (=Genkwanin)	C ₁₆ H ₁₂ O ₅	<i>Marchantia polymorpha</i> (8)
1912	Apigenin-4'-methyl ether (=Acacetin)	C ₁₆ H ₁₂ O ₅	<i>Frullania teneriffae</i> (444)
1913	Apigenin-7,4'-dimethyl ether	C ₁₇ H ₁₄ O ₅	<i>Frullania teneriffae</i> (330)
			<i>Plagiochila buchtiniana</i> (330)
			<i>Plagiochila diversifolia</i> (330)
			<i>Plagiochila longispina</i> (330)
			<i>Frullania muscicola</i> (484)
			<i>Marchesinia brachiata</i> (594)
			<i>Plagiochila buchtiniana</i> (330)

(continued)

Table 4.8 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1914	Apigenin-7-O-glucuronide	$\text{C}_{21}\text{H}_{18}\text{O}_{11}$			<i>Plagiochila diversifolia</i>	(330)	
					<i>Plagiochila longispina</i>	(330)	
					<i>Trocholejeunea sandvicensis</i>	(460)	
					<i>Marchantia palmata</i>	(193)	
1915	Apigenin-7-O- β -D-glucoside	$\text{C}_{21}\text{H}_{20}\text{O}_{10}$			<i>Blasia pusilla</i>	(971)	
1916	5-Hydroxy-7,8,4'-trimethoxyflavone (= Isoscutellarein-7,8,4'-trimethyl ether)	$\text{C}_{18}\text{H}_{16}\text{O}_6$			<i>Asterella blumeana</i>	(619)	<i>in vitro</i>
1917	Scutellarein-6-methyl ether	$\text{C}_{16}\text{H}_{12}\text{O}_6$	280-284		<i>Frullania muscicola</i>	(484)	Cultures
1918	Scutellarein-6,4'-dimethyl ether	$\text{C}_{17}\text{H}_{14}\text{O}_6$	223-224		<i>Frullania muscicola</i>	(484)	
1919	5,7,4'-Trihydroxy-6,3'-dimethoxyflavone (= Jaceosidin)	$\text{C}_{17}\text{H}_{14}\text{O}_7$	232-234		<i>Frullania muscicola</i>	(484)	
1920	Quercetin	$\text{C}_{15}\text{H}_{10}\text{O}_7$			<i>Lunularia cruciata</i>	(371)	
1921	5,3',4'-trihydroxyisoflavone-7-O- β -D-glucopyranoside (= Orobol-7-O-glucoside)	$\text{C}_{21}\text{H}_{20}\text{O}_{11}$			<i>Marchantia polymorpha</i>	(667)	
1922	5-Hydroxy-7-methoxyflavone	$\text{C}_{16}\text{H}_{12}\text{O}_4$			<i>Tylimanthus renifolius</i>	(213)	
1923	5,7-Dimethoxyflavone	$\text{C}_{17}\text{H}_{14}\text{O}_4$			<i>Tylimanthus renifolius</i>	(213)	
1924	5-Hydroxy-6,7-dimethoxyflavone	$\text{C}_{17}\text{H}_{14}\text{O}_5$			<i>Tylimanthus renifolius</i>	(213)	

1925	6-Hydroxy-5,7-dimethoxyflavone	C ₁₇ H ₁₄ O ₅	<i>Tylimanthus renifolius</i>	(213)
1926	5,7-Dihydroxy-6-methoxyflavone	C ₁₆ H ₁₂ O ₅	<i>Tylimanthus renifolius</i>	(213)
1927	5-Hydroxy-7,4'-dimethoxyflavone	C ₁₇ H ₁₄ O ₅	<i>Frullania hamatiloba</i>	(316)
1928	5,6,7-Trimethoxyflavone	C ₁₈ H ₁₆ O ₅	<i>Frullania squarrosula</i>	(84)
			<i>Tylimanthus renifolius</i>	(213)
1929	5-Hydroxy-7-methoxyflavanone (=Pinostrobin)	C ₁₆ H ₁₄ O ₄	<i>Tylimanthus renifolius</i>	(213)
1930	5,7-Dimethoxyflavanone	C ₁₇ H ₁₆ O ₄	<i>Tylimanthus renifolius</i>	(213)
1931	5-Hydroxy-6,7-dimethoxyflavanone	C ₁₇ H ₁₆ O ₅	<i>Tylimanthus renifolius</i>	(213)
1932	5,6,7-Trimethoxyflavanone	C ₁₈ H ₁₈ O ₅	<i>Tylimanthus renifolius</i>	(213)
1933	5,7,4'-Trimethoxyflavanone	C ₁₈ H ₁₈ O ₅	<i>Frullania hamatiloba</i>	(316)
1934	Riccioniidin A	C ₁₅ H ₉ O ₆	<i>Marchantia polymorpha</i>	(454)
			<i>Riccia duplex</i>	(454)
			<i>Ricciocarpos natans</i>	(454)
			<i>Scapania undulata</i>	(454)
			<i>Marchantia polymorpha</i>	(454)
1935	Riccioniidin B	C ₃₀ H ₁₇ O ₁₂	<i>Riccia duplex</i>	(454)
			<i>Ricciocarpos natans</i>	(454)
			<i>Scapania undulata</i>	(454)

The ether extract of the sporophytes of *Pellia epiphylla* was purified by column chromatography to give the new flavone, luteolin-5,7,3'-trimethyl ether (**1893**), along with the known luteolin (**1888**), luteolin-7-methyl ether (**1889**), and luteolin-7,3'-dimethyl ether (= velutin) (**1890**). The methoxy substituents in compound **1893** were located using a NOESY experiment (**175**).

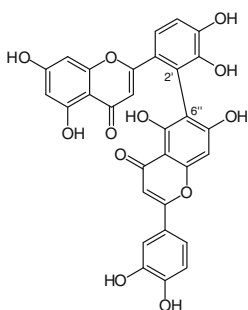
The re-fractionation of the methanol extract of *Dumortiera hirsuta* resulted in the isolation of the new flavone glycoside luteolin-5-*O*- β -D-glucuronide-6''-methyl ester (**1896**), along with the known luteolin (**1888**), luteolin-5-*O*-glucuronide (**1894**), and luteolin-7-*O*-glucuronide (**1895**) (**445**).

A dichloromethane extract of *Frullania teneriffae* was purified by HPLC to give luteolin-7,3'-dimethyl ether (**1890**), luteolin-3',7'-dimethyl ether (**1891**), luteolin-7,3',4'-trimethyl ether (**1892**), apigenin-7-methyl ether (= genkwanin) (**1911**), and apigenin-4'-methyl ether (= acacetin) (**1912**). At the time of their isolation, genkwanin and acacetin were unknown as free aglycones among the bryophytes. In addition to the above aglycones, also isolated were luteolin-7-*O*-neohesperidoside (**1900**), acylated luteolin-7-*O*-neohesperidosides for which the acyl parts remained to be clarified, luteolin-6-*O*-glucosyl-7-*O*-glucoside (**1901**), luteolin-6-*O*-glucosyl-7-*O*-glucosyl-6'''-3-hydroxy-3-methylglutaric acid (**1902**), and nodiforetin-6-*O*-glucosyl-7-*O*-glucoside acylated at the 7-*O*-glucose unit. The structures of all flavonoids isolated were determined by interpretation of their UV, FAB-MS, and ¹H NMR and ¹³C NMR data. The constituents of *Frullania cesatiana* were isolated and the structures of three isolated flavonoids were assigned as luteolin-6,8-di-*C*- β -D-glucopyranoside (= lucenin 2) (**1903**), an unidentified lucenin-2 derivative, and the new 6-hydroxyluteolin-7-*O*- β -D-glucosyl-6''-(3-hydroxy-3-methylglutaric acid ester)-3-*O*-glucuronide (**1904**), by means of their UV/vis, FAB-MS, ¹H NMR spectroscopic, and chromatographic data. The phenolic profile of *Frullania eboracensis* was almost identical to that of *F. muscicola*. Both species have been found to contain glycerol-1-*O*-glucosyl-4'-caffeoyl ester and flavonoids. A flavonoid constituent of *Frullania gibbosa* and *F. arecae* was characterized as 6-hydroxyluteolin-7-*O*- β -glucopyranosyl-6''-(3-hydroxy-3-methylglutaric acid ester)-3'-*O*-glucuronide (**1904**) (**444**), which was also the main flavonoid of *F. muscicola* (**40**).

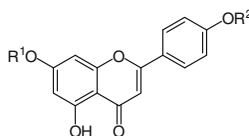
Monoclea species belonging to the Monocleaceae are giant thalloid liverworts growing only in the southern hemisphere, particularly in New Zealand and South America. Markham reported that *M. forsteri* produces a unique flavone polyglycoside compound, MF-1, for which the structure remained to be fully clarified when isolated initially (**506**). Reinvestigation of this isolate showed that MF-1 is a mixture (MF-1a and MF-1b) of penta- and hexa-*O*-glycosides of 6-methoxyluteolin, but having no 8-methoxyluteolin components present. On the basis of the NMR spectra, including TOCSY and COSY experiments, and using the mass spectrometric data, and the confirmation of each sugar moiety obtained by hydrolysis, the structures of MF-1a and MF-1b were determined as 6-methoxyluteolin 7-*O*-[2-*O*- α -rhamnosyl-3-*O*- α -arabinosyl- β -glucuronide]-4'-*O*-[2-*O*- α -rhamnosyl-3-*O*- β -xylosyl- β -glucuronide] (**1905**) and 6-methoxyluteolin-7-*O*-[2-*O*- α -rhamnosyl- β -glucuronide]-4'-*O*-[2-*O*- α -rhamnosyl-3-*O*- β -xylosyl- β -glucuronide]

(1906) (510). Two additional minor flavone polysaccharides (MF-1a' and MF-1b') were detected from the same species by HPLC, with their structures deduced as luteolin 7-*O*-[2-*O*- α -rhamnosyl-3-*O*- α -arabinosyl- β -glucuronide]-4'-*O*-[2-*O*- α -rhamnosyl-3-*O*- β -xylosyl- β -glucuronide] (1907) and luteolin 7-*O*-[2-*O*- α -rhamnosyl- β -glucuronide]-4'-*O*-[2-*O*- α -rhamnosyl-3-*O*- β -xylosyl- β -glucuronide] (1908), from their NMR and mass spectra. This was the first report of the occurrence of flavone penta- and hexa-*O*-glucosides in Nature (510).

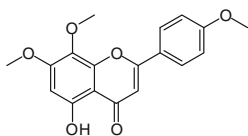
The aqueous methanol extract of *Chandonanthus hirtellus* subsp. *giganteus* was purified by column chromatography to give luteolin (1888) and a biflavone, dicranolomin (= 2',6''-bisluteolin) (1909), which was also found in the moss *Dicranoloma robustum* (40). This was the first isolation of a biflavone from the liverworts. Biflavones are considered to be significant chemotaxonomic markers for mosses (441).



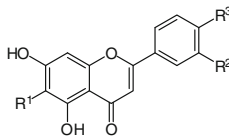
1909 (dicranolomin (=2',6''-bisluteolin))



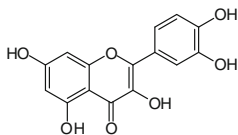
- 1910 $R^1=R^2=H$ (apigenin)
 1911 $R^1=Me$, $R^2=H$ (apigenin-7-methyl ether (= genkwanin))
 1912 $R^1=H$, $R^2=Me$ (apigenin-4'-methyl ether (= acacetin))
 1913 $R^1=R^2=Me$ (apigenin-7,4'-dimethyl ether)
 1914 $R^1=GlcA$, $R^2=H$ (apigenin-7-*O*-glucuronide)
 1915 $R^1=Glc$, $R^2=H$ (apigenin-7-*O*- β -glucoside)



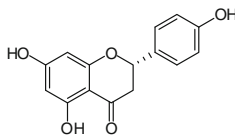
1916 (isoscutellarein-7,8,4'-trimethyl ether)



- 1917 $R^1=OMe$; $R^2=H$; $R^3=OH$ (scutellarein-6-methyl ether)
 1918 $R^1=R^3=OMe$; $R^2=H$ (scutellarein-6,4'-dimethyl ether)
 1919 $R^1=R^2=OMe$; $R^3=OH$
 (5,7,4'-trihydroxy-6,3'-dimethoxyflavone (= jaceosidin))



1920 (quercetin)

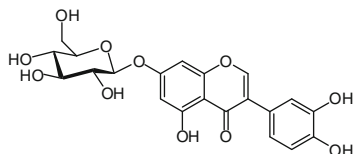


1920a (naringenin)

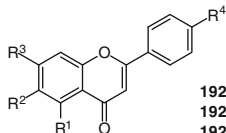
Flavonoids found in the Marchantiophyta

Luteolin (1888) and apigenin (1910) was identified in the methanol extract of sterile cultures of *Marchantia polymorpha* (8). Dixit and Srivastava also confirmed the presence of luteolin-3'-*O*- β -D-glucuronide (1897), luteolin-7,3'-di-*O*-

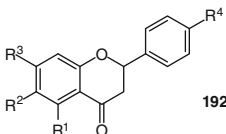
β -D-glucuronide (**1898**), apigenin-7-*O*-glucuronide (**1914**) and their aglycones, **1888** and **1910** in *M. palmata* (**193**).



1921 (5,3',4'-trihydroxyisoflavone-7-*O*- β -D-glucopyranoside
(= orobol-7-*O*-glucoside))



- 1922** R¹=OH, R²=R⁴=H, R³=OMe (5-hydroxy-7-methoxyflavone)
1923 R¹=R³=OMe, R²=R⁴=H (5,7-dimethoxyflavone)
1924 R¹=OH, R²=R³=OMe, R⁴=H (5-hydroxy-6,7-dimethoxyflavone)
1925 R¹=R³=OMe, R²=OH, R⁴=H (6-hydroxy-5,7-dimethoxyflavone)
1926 R¹=R³=OH, R²=OMe, R⁴=H (5,7-dihydroxy-6-methoxyflavone)
1927 R¹=OH, R²=H, R³=R⁴=OMe (5-hydroxy-7,4'-dimethoxyflavone)
1928 R¹=R²=R³=OMe, R⁴=H (5,6,7-trimethoxyflavone)



- 1929** R¹=OH, R²=R⁴=H, R³=OMe (5-hydroxy-7-methoxyflavanone
(=pinostrobin))
1930 R¹=R³=OMe, R²=R⁴=H (5,7-dimethoxyflavanone)
1931 R¹=OH, R²=R³=OMe, R⁴=H (5-hydroxy-6,7-dimethoxyflavanone)
1932 R¹=R²=R³=OMe, R⁴=H (5,6,7-trimethoxyflavanone)
1933 R¹=R³=R⁴=OMe, R²=H (5,7,4'-trimethoxyflavanone)

Flavonoids found in the Marchantiophyta

Apigenin-7,4'-dimethyl ether (**1913**) and apigenin-7-*O*- β -D-glucoside (**1915**) were also isolated from *Trocholejeunea sandvicensis* (**460**) and *Blasia pusilla* (**971**).

From *in vitro* cultures of *Asterella blumeana*, the flavone, 5-hydroxy-7,8,4'-trimethoxyflavone (= isoscutellarein-7,8,4'-trimethyl ether) (**1916**) was isolated (**619**). This compound has been also isolated from the liverwort *Reboulia hemisphaerica* (**549**).

Frullania muscicola also produced three flavones, scutellarein-6-methyl ether (**1917**), scutellarein-6,4'-dimethyl ether (**1918**), and 5,7,4'-trihydroxy-6,3'-dimethylflavone (= jaceosidin) (**1919**) (**484**).

The methanol extract of *Lunularia cruciata* was analyzed by means of reversed-phase HPLC equipped with a diode-array detector to identify luteolin-7-*O*-glucoside (**1899**) and quercetin (**1920**) (**371**).

Marchantia polymorpha produces not only a large amount of bis-bibenzylyls but also aurone and flavone flavonoids, with the latter group comprising apigenin and luteolin *O*- β -glucuronides and other apigenin and luteolin *O*-glycosides (**40**). Chalcone synthase activity was measured in gametophyte tissue of *M. polymorpha*. The main product of the enzymatic reaction was confirmed as the flavanone naringenin (**1920a**), which results from cyclization of a chalcone. It has been clarified that *M. polymorpha* contains a chalcone synthase protein (**225**). *Qu* and

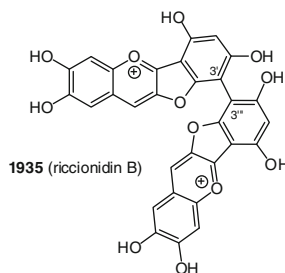
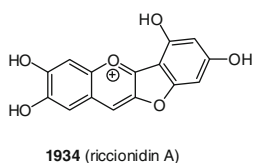
associates reported the isolation of 5,3',4'-trihydroxy-7-*O*- β -D-glucopyranoside (= orbol-7-*O*-glucoside) (**1921**) from *M. polymorpha* (667).

Tylimanthus renifolius produces flavones and flavanones with an unsubstituted B-ring as the major components. Compounds identified included 5-hydroxy-7-methoxyflavone (**1922**), 5,7-dimethoxyflavone (**1923**), 5-hydroxy-6,7-dimethoxyflavone (**1924**), 6-hydroxy-5,7-dimethoxyflavone (**1925**), 5,7-dihydroxy-6-methoxyflavone (**1926**), 5,6,7-trimethoxyflavone (**1928**), 5-hydroxy-7-methoxyflavanone (= pinostrobin) (**1929**), 5,7-dimethoxyflavanone (**1930**), 5-hydroxy-6,7-dimethoxyflavanone (**1931**), and 5,6,7-trimethoxyflavanone (**1932**) (213). This represented the first isolation of such flavonoids from the bryophytes.

Apigenin-7,4'-dimethyl ether (**1913**), 5-hydroxy-7,4'-dimethoxyflavone (**1927**) and 5,7,4'-trimethoxyflavone (**1933**) were isolated from the ether extract of *Frullania hamatiloba* (316). The 5-methoxyflavones are very rare in the liverworts. Compound **1927** has been also found in the New Zealand *Frullania squarrosula* (84).

4.6.2 Anthocyanins

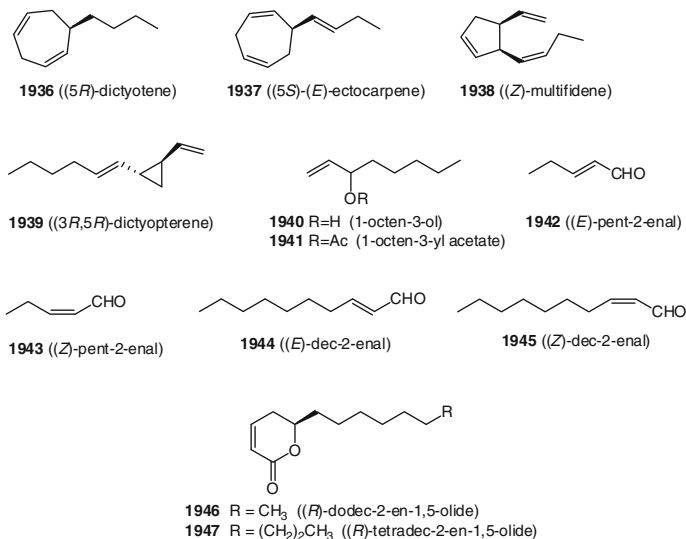
A new anthocyanidin named riccionidin A (**1934**) and a dimer, riccionidin B (**1935**), were isolated from the cell walls of *Ricciocarpos natans* grown in axenic culture. The structure of the pigment **1934** was assigned by the presence of a signal at δ 9.06 ppm, characteristic for the proton on C-4 of a flavylium ion. The assignments of four proton signals as well as the substitution pattern were made by analysis of NMR data including the ^1H - ^{13}C COSY spectrum. The dimeric nature of **1935** was based on HR-FAB-MS, which showed the molecular formula to be $\text{C}_{30}\text{H}_{17}\text{O}_{12}$ (m/z 569.0783). The ^1H and ^{13}C NMR spectra suggested that **1935** might contain anthocyanidin units of compound **1934** connected between the C-3' or C-5' positions (454). Compounds **1934** and **1935** were detected in the other liverworts, *Marchantia polymorpha*, *Riccia duplex*, and *Scapania undulata* (454). The formation of such cell wall pigments was shown to be dependent upon the level of the nutrients and the light intensity. High levels of sucrose and phosphate were found to inhibit pigment formation, whereas a decrease in nitrogen supply induced the formation of riccionidin A (**1934**) (451).



Dyker and *Bauer* achieved the total synthesis of riccionidin A (1934) by the condensation reaction of 2,4,5-trihydroxybenzaldehyde and 4,6-dihydroxydihydrobenzofuran-3-one in acetic acid and hydrogen chloride (199)

4.7 Acetogenins and Lipids

The Greek *Fossombronina angulosa* is chemically very characteristic, since this species produces the three acetogenins, dictyotene (1936), (*Z*)-multifidene (1938), and dictyopterene (1939) (492), which were all previously isolated from a brown algal source (383). The volatile components of the French Polynesian *Chandonanthus hirtellus* were analyzed by GC/MS to confirm the presence of dictyotene (1936) and ectocarpene (1937) (423, 494). In addition, (–)-(*R*)-dictyotene (1936), (+)-(*S*)-ectocarpene (1937), and (+)-(3*R*,5*R*)-dictyopterene (1939) were isolated from *Fossombronina angulosa* collected in the islands of Tenerife and Madeira and their structures elucidated from the ¹H and ¹³C NMR spectra, with the use of GC having a modified cyclodextrin as stationary phase (919). The distribution of acetogenins 1936–1939 in the Marchantiophyta is very significant in considering the phylogeny of terrestrial spore-forming plants and their evolutionary processes (see Chap. 9).



Acetogenins found in the Marchantiophyta

A number of liverworts contain 1-octen-3-ol (1940) and/or 1-octen-3-yl acetate (1941), as shown in Table 4.9. *Rycroft* and *Cole* found all of the new and old specimens of *Plagiochila rutilans* and *P. standleyi* they examined to contain the latter acetate (693). The presence of 1-octen-3-ol (1940) and 1-octen-3-yl acetate (1941) in Canadian and Japanese samples of *Herbertus sakuraii* has been confirmed by GC/MS (323). Further investigation of the essential oil of *Lophozia ventricosa* resulted in the identification of 1-octen-3-ol (1940) and 1-octen-3-yl acetate (1941) in trace amounts (486).

Table 4.9 Acetogenins and lipids found in the Marchantiophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1936	Dictyotene	$\text{C}_{11}\text{H}_{18}$			<i>Chandonanthus hirtellus</i>	(423)	
						(494)	
1937	(E)-Ectocarpene	$\text{C}_{11}\text{H}_{16}$			<i>Fossombronina angulosa</i>	(492)	
					<i>Chandonanthus hirtellus</i>	(423)	
						(494)	
1938	(Z)-Multifidene	$\text{C}_{11}\text{H}_{16}$			<i>Fossombronina angulosa</i>	(492)	
1939	Dictyopterene	$\text{C}_{11}\text{H}_{18}$			<i>Fossombronina angulosa</i>	(492)	
1940	1-Octen-3-ol	$\text{C}_8\text{H}_{16}\text{O}$			<i>Asterella africana</i>	(222)	
					<i>Asterella tenera</i>	(72)	
					<i>Chandonanthus hirtellus</i>	(224)	
					<i>Conocephalum conicum</i>	(880)	
					<i>Herbertus sakuraii</i>	(323)	
					<i>Lophozia ventricosa</i>	(486)	
					<i>Marsupella alpina</i>	(17)	
					<i>Marsupella emarginata</i>	(17)	
					<i>Mastigophora diclados</i>	(287)	
						(425)	
						(494)	
					<i>Plagiochila bifaria</i>	(221)	
					<i>Plagiochila maderensis</i>	(221)	
					<i>Plagiochila retrorsa</i>	(221)	
					<i>Plagiochila stricta</i>	(221)	
					<i>Radula aquilegia</i>	(223)	
					<i>Radula jonesii</i>	(223)	
					<i>Radula lindenbergiana</i>	(223)	
					<i>Radula nudicaulis</i>	(223)	
					<i>Radula wichurae</i>	(223)	

(continued)

1942	(E)-Pent-2-enal	C ₅ H ₈ O	<i>Plagiochila sciophila</i>	(492)
1943	(Z)-Pent-2-enal	C ₅ H ₈ O	<i>Plagiochila standleyi</i>	(494)
1944	(E)-Dec-2-enal	C ₁₀ H ₁₈ O		(693)
1945	(Z)-Dec-2-enal	C ₁₀ H ₁₈ O	<i>Plagiochila stricta</i>	(221)
1946	(R)-Dodec-2-en-1,5-olide	C ₁₂ H ₂₀ O ₂	<i>Trichocolea pluma</i>	(494)
1947	(R)-Tetradec-2-en-1,5-olide	C ₁₄ H ₂₄ O ₂	<i>Wiesnerella denudata</i>	(492)
1948	2-[(8'Z,11'Z)-Hexadecadienyl]-penta-2,4-dien-1,4-olide	C ₂₁ H ₃₂ O ₂	<i>Chiloscyphus pallidus</i>	(72)
1949	2-[(8'Z)-Hexadecenyl]-penta-2-en-1,4-olide	C ₂₁ H ₃₄ O ₂	<i>Chiloscyphus pallidus</i>	(72)
1950	2-[(7'Z,10'Z,13'Z)-Hexadecatrienyl]-penta-2,4-dien-1,4-olide	C ₂₁ H ₃₀ O ₂	<i>Chiloscyphus pallidus</i>	(72)
1951	2β-[(7'Z,10'Z,13'Z)-Hexadecatrienyl]-3β-hydroxypenta-4-en-1,4-olide	C ₂₁ H ₃₂ O ₃	<i>Cheilolejeunea imbricata</i>	(879)
1951a	β- <i>n</i> -Octyl-γ-butanolide	C ₁₂ H ₂₂ O ₂	<i>Cheilolejeunea imbricata</i>	(879)
1952	<i>n</i> -Heptanal	C ₇ H ₁₄ O	<i>Marchantia paleacea</i> var. <i>diptera</i>	(347)
1953	<i>n</i> -Nonanal	C ₉ H ₁₈ O	<i>Marchantia paleacea</i> var. <i>diptera</i>	(347)
1954	Octan-3-one	C ₈ H ₁₆ O	<i>Marchantia emarginata</i> subsp. <i>tosana</i>	(877)
			<i>Marchantia foliacea</i>	(347)
			<i>Marchantia emarginata</i> subsp. <i>tosana</i>	(347)
			<i>Marchantia paleacea</i>	(424)
			<i>Asterella africana</i>	(877)
			<i>Asterella africana</i>	(424)
			<i>Radula carringtonii</i>	(222)
			<i>Radula lindenbiana</i>	(222)
			<i>Radula nudicaulis</i>	(223)
			<i>Radula wichurae</i>	(223)
			<i>Marsipella emarginata</i>	(17)

(continued)

Table 4.9 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1955	2-Undecanone	$\text{C}_{11}\text{H}_{22}\text{O}$			<i>Adelanthus decipiens</i> <i>Asterella africana</i> <i>Frullania solanderiana</i> <i>Plagiochilla bifaria</i>	(693) (222) (78) (333)	
1956	2-Tridecanone	$\text{C}_{13}\text{H}_{26}\text{O}$			<i>Frullania solanderiana</i> <i>Fossombronina angulosa</i>	(78) (492)	
1957	Tetradecane	$\text{C}_{14}\text{H}_{30}$			<i>Metzgeria temperata</i>	(882)	
1958	1-Tetradecanol	$\text{C}_{14}\text{H}_{30}\text{O}$			<i>Frullania solanderiana</i>	(78)	
1959	2-Pentadecanone	$\text{C}_{15}\text{H}_{30}\text{O}$			<i>Frullania solanderiana</i>	(78)	
1960	Hexadecane	$\text{C}_{16}\text{H}_{34}$			<i>Metzgeria temperata</i>	(882)	
1961	1-Heptadecene	$\text{C}_{17}\text{H}_{34}$			<i>Frullania chevalieri</i>	(78)	
1962	Heptadecane	$\text{C}_{17}\text{H}_{36}$			<i>Chandonanthus hirtellus</i> <i>Lepidozia reptans</i>	(423) (195)	
1963	Octadecane	$\text{C}_{18}\text{H}_{38}$			<i>Scapania temperata</i>	(195)	
1964	1-Octadecanol	$\text{C}_{18}\text{H}_{38}\text{O}$			<i>Lepidozia reptans</i> <i>Metzgeria temperata</i> <i>Pellia epiphylla</i>	(195) (882) (175)	Sporophyte and spores
1965	16-Octadecenal	$\text{C}_{18}\text{H}_{34}\text{O}$			<i>Frullania scandens</i>	(78)	
1966	17-Octadecenal	$\text{C}_{18}\text{H}_{34}\text{O}$			<i>Frullania scandens</i>	(78)	
1967	Elaidic alcohol (=9-Octadecen-1-ol)	$\text{C}_{18}\text{H}_{36}\text{O}$			<i>Lepidozia reptans</i>	(195)	
1968	Nonadecane	$\text{C}_{19}\text{H}_{40}$			<i>Lepidozia reptans</i>	(195)	
1969	Eicosane	$\text{C}_{20}\text{H}_{42}$			<i>Metzgeria temperata</i>	(882)	
1970	Heneicosane	$\text{C}_{21}\text{H}_{44}$			<i>Metzgeria temperata</i> <i>Frullania probosciphora</i>	(882) (78)	

1971	Docosane	C ₂₂ H ₄₆	<i>Frullania probosciphora</i> (78)
			<i>Frullania scandens</i> (78)
			<i>Lepidozia reptans</i> (195)
			<i>Frullania scandens</i> (78)
1972	1-Docosene	C ₂₂ H ₄₄	<i>Metzgeria temperata</i> (882)
1973	Tricosane	C ₂₃ H ₄₈	<i>Frullania scandens</i> (78)
1974	Tetracosane	C ₂₄ H ₅₀	<i>Frullania scandens</i> (78)
1975	Pentacosane	C ₂₅ H ₅₂	<i>Metzgeria temperata</i> (882)
			<i>Metzgeria temperata</i> (882)
1976	Heptacosane	C ₂₇ H ₅₆	<i>Scapania calcicolea</i> (194)
			<i>Metzgeria temperata</i> (882)
1977	Nonacosane	C ₂₉ H ₆₀	<i>Pellia neesiana</i> (190)
1978	Lauric acid (12:0)	C ₁₂ H ₂₄ O ₂	<i>Riccia fluitans</i> (78)
	(=Dodecanoic acid)		<i>Frullania pycnantha</i> (78)
1979	Tridecanoic acid (13:0)	C ₁₃ H ₂₆ O ₂	<i>Frullania anomala</i> (78)
1980	Myristic acid (14:0)	C ₁₄ H ₂₈ O ₂	<i>Frullania incumbens</i> (78)
	(=Tetradecanoic acid)		<i>Frullania lobulata</i> (78)
			<i>Frullania probosciphora</i> (78)
			<i>Frullania scandens</i> (78)
			<i>Frullania spinifera</i> (78)
			<i>Pellia neesiana</i> (190)
			<i>Plagiochila tabinensis</i> (331)
1981	Pentadecanoic acid (15:0)	C ₁₅ H ₃₀ O ₂	<i>Riccia fluitans</i> (190)
			<i>Pellia neesiana</i> (190)
			<i>Plagiochila tabinensis</i> (331)
			<i>Riccia fluitans</i> (190)
1982	Palmitic acid (16:0)	C ₁₆ H ₃₂ O ₂	<i>Apometzgeria pubescens</i> (882)
	(=Hexadecanoic acid)		<i>Chandonanthus hirtellus</i> (224)
			<i>Conocephalum conicum</i> (731)
			<i>Frullania falciloba</i> (78)

(continued)

Table 4.9 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
					<i>Frullania solanderiana</i>	(78)	
					<i>Frullania chevalierii</i>	(78)	
					<i>Herbertus adancus</i> subsp. <i>hutchinsiae</i>	(137)	
					<i>Isotachis aubertii</i>	(288)	
					<i>Lepidozia reptans</i>	(195)	
					<i>Lepidozia virrea</i>	(746)	
					<i>Marchantia polymorpha</i>	(492)	Cultured cells
						(709)	Sporophyte
					<i>Pellia epiphylla</i>	(175)	Sporophyte
						(492)	
					<i>Pellia neestiana</i>	(190)	
					<i>Plagiochila elegans</i>	(470)	
					<i>Plagiochila tabinensis</i>	(331)	
					<i>Radula aquilegia</i>	(223)	
					<i>Radula boryana</i>	(224)	
					<i>Radula nudicaulis</i>	(223)	
					<i>Riccia fluitans</i>	(190)	
					<i>Ricciocarpos natans</i>	(974)	
					<i>Scapania calcicolea</i>	(194)	
					<i>Isotachis aubertii</i>	(288)	
					<i>Lepidozia reptans</i>	(195)	
					<i>Scapania calcicolea</i>	(194)	
					<i>Trichocolea pluma</i>	(494)	
					<i>Marchantia polymorpha</i>	(492)	Sporophyte
					<i>Plagiochila elegans</i>	(470)	
					<i>Trichocolea pluma</i>	(494)	
1983	Methyl palmitate (=Hexadecanoic acid methyl ester)	C ₁₇ H ₃₄ O ₂					
1984	Ethyl palmitate (=Hexadecanoic acid ethyl ester)	C ₁₈ H ₃₆ O ₂					

1985	Butyl hexadecanoate	C ₂₀ H ₄₀ O ₂	<i>Lepidozia reptans</i> (195)
1986	Heptadecanoic acid (17:0)	C ₁₇ H ₃₄ O ₂	<i>Scapania calcicola</i> (194)
			<i>Pellia neesiana</i> (190)
			<i>Plagiochila tabinensis</i> (331)
			<i>Riccia fluitans</i> (190)
1987	Butyl heptadecanoate	C ₂₁ H ₄₂ O ₂	<i>Lepidozia reptans</i> (195)
1988	Stearic acid (18:0) (=Octadecanoic acid)	C ₁₈ H ₃₆ O ₂	<i>Conocephalum conicum</i> (731)
			<i>Frullania incumbens</i> (78)
			<i>Frullania lobulata</i> (78)
			<i>Frullania magellanica</i> (78)
			<i>Herbertus adancus</i> subsp. <i>hutchinsiae</i> (137)
			<i>Lepidozia reptans</i> (195)
			<i>Marchantia polymorpha</i> (709)
			<i>Pellia neesiana</i> (190)
			<i>Plagiochila tabinensis</i> (331)
			<i>Riccia fluitans</i> (190)
			<i>Ricciocarpos natans</i> (974)
			<i>Scapania calcicola</i> (194)
			<i>Herbertus adancus</i> subsp. <i>hutchinsiae</i> (137)
1989	Isostearic acid	C ₁₈ H ₃₆ O ₂	<i>Scapania calcicola</i> (194)
1990	Methyl octadecanoate	C ₁₉ H ₃₈ O ₂	<i>Scapania calcicola</i> (194)
1991	Butyl octadecanoate	C ₂₂ H ₄₄ O ₂	<i>Lepidozia reptans</i> (195)
1992	Arachidic acid (20:0) (=Eicosanoic acid)	C ₂₀ H ₄₀ O ₂	<i>Pellia neesiana</i> (190)
			<i>Plagiochila tabinensis</i> (331)
			<i>Riccia fluitans</i> (190)
1993	Methyl docosanoate	C ₂₃ H ₄₆ O ₂	<i>Scapania calcicola</i> (194)
1994	Methyl tetracosanoate	C ₂₅ H ₅₀ O ₂	<i>Plagiochila tabinensis</i> (331)
			<i>Scapania calcicola</i> (194)

(continued)

Table 4.9 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1995	Methyl hexacosanoate	C ₂₇ H ₅₄ O ₂			<i>Plagiochila atlantica</i>	(334)	
1996	9-Tridecenoic acid (13:1n-4)	C ₁₃ H ₂₄ O ₂			<i>Pellia neesiana</i>	(190)	
					<i>Riccia fluitans</i>	(190)	
1997	7-Pentadecenoic acid (15:1n-8)	C ₁₅ H ₂₈ O ₂			<i>Pellia neesiana</i>	(190)	
					<i>Riccia fluitans</i>	(190)	
1998	7-Hexadecenoic acid (16:1n-9)	C ₁₆ H ₃₀ O ₂			<i>Pellia neesiana</i>	(190)	
					<i>Riccia fluitans</i>	(190)	
1999	Palmitoleic acid (16:1n-7) (=9-Hexadecenoic acid)	C ₁₆ H ₃₀ O ₂			<i>Marchantia polymorpha</i>	(709)	
2000	8-Heptadecenoic acid (17:1n-9)	C ₁₇ H ₃₂ O ₂			<i>Plagiochila tabinensis</i>	(331)	
					<i>Pellia neesiana</i>	(190)	
2001	7-Octadecenoic acid (18:1n-11)	C ₁₈ H ₃₄ O ₂			<i>Riccia fluitans</i>	(190)	
					<i>Pellia neesiana</i>	(190)	
2002	Oleic acid (18:1n-9) (=9-Octadecenoic acid)	C ₁₈ H ₃₄ O ₂			<i>Riccia fluitans</i>	(190)	
					<i>Frullania anomala</i>	(78)	
					<i>Frullania incumbens</i>	(78)	
					<i>Frullania magellanica</i>	(78)	
					<i>Marchantia polymorpha</i>	(709)	
2003	Methyl 9-octadecenoate	C ₁₉ H ₃₆ O ₂			<i>Plagiochila tabinensis</i>	(331)	
2004	11-Octadecenoic acid (18:1n-7)	C ₁₈ H ₃₄ O ₂			<i>Scapania calcivolea</i>	(194)	
					<i>Pellia neesiana</i>	(190)	
					<i>Riccia fluitans</i>	(190)	
2005	6-Octadecynoic acid (6a-18:1) (=Tarric acid)	C ₁₈ H ₃₂ O ₂			<i>Pellia neesiana</i>	(190)	
2006	9-Octadecynoic acid (9a-18:1) (=Stearolic acid)	C ₁₈ H ₃₂ O ₂			<i>Riccia fluitans</i>	(190)	
2007	12-Octadecynoic acid (12a-18:1)	C ₁₈ H ₃₂ O ₂			<i>Pellia neesiana</i>	(190)	
					<i>Riccia fluitans</i>	(190)	

Cultured cells

Cultured cells

2008	7,10,13-Hexadecatrienoic acid (16:3n-3)	$C_{16}H_{26}O_2$	<i>Conocephalum conicum</i> <i>Pellia neesiana</i> <i>Riccia fluitans</i> <i>Ricciocarpos natans</i> <i>Pellia epiphylla</i> <i>Pellia neesiana</i> <i>Riccia fluitans</i> <i>Pellia neesiana</i> <i>Riccia fluitans</i> <i>Apometzgeria pubescens</i> <i>Chandonanthus hirtellus</i> <i>Conocephalum conicum</i> <i>Frullania anomala</i> <i>Frullania incumbens</i> <i>Frullania lobulata</i> <i>Frullania probosciphora</i> <i>Frullania pycnantha</i> <i>Frullania scandens</i> <i>Frullania solanderiana</i> <i>Frullania spinifera</i> <i>Marchantia polymorpha</i> <i>Marchantia polymorpha</i> <i>Plagiochila tabinensis</i> <i>Radula nudicaulis</i> <i>Ricciocarpos natans</i> <i>Pellia epiphylla</i> <i>Chandonanthus hirtellus</i>	(731) (190) (190) (974) (175) (190) (190) (190) (190) (882) (224) (731) (78) (78) (78) (78) (78) (78) (78) (78) (78) (492) (709) (331) (223) (974) (175) (423) (494)	Sporophyte
2009	Methyl 7,10,13-hexadecatrienoate	$C_{17}H_{28}O_2$			
2010	4,7,10-Hexadecatrienoic acid (16:3n-6)	$C_{16}H_{26}O_2$			
2011	4,7,10,13-Hexadecatetraenoic acid (16:4n-3)	$C_{16}H_{24}O_2$			
2012	Linoleic acid (18:2n-6) (=9,12-Octadecadienoic acid)	$C_{18}H_{32}O_2$			
2013	Methyl linoleate (=Methyl 9,12-octadecadienoate)	$C_{19}H_{34}O_2$			Sporophyte Cultured cells
2014	Ethyl linoleate (=Ethyl 9,12-Octadecadienoate)	$C_{20}H_{36}O_2$			Sporophyte

(continued)

Table 4.9 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\text{10}^{-1}$	Plant source(s)	Reference(s)	Comments
2015	12,15-Octadecadienoic acid (18:2n-3)	$\text{C}_{18}\text{H}_{32}\text{O}_2$			<i>Pellia neesiana</i>	(190)	
2016	11,14-Octadecadienoic acid (18:2n-4)	$\text{C}_{18}\text{H}_{32}\text{O}_2$			<i>Riccia fluitans</i> <i>Ricciocarpos natans</i>	(190) (974)	
2017	α -Linolenic acid (18:3n-3) (=9,12,15-Octadecatrienoic acid)	$\text{C}_{18}\text{H}_{30}\text{O}_2$			<i>Apometzgeria pubescens</i> <i>Conocephalum conicum</i> <i>Frullania probosciphora</i> <i>Herbertus adancus</i> subsp. <i>hutchinsiae</i> <i>Lepidozia reptans</i> <i>Marchantia polymorpha</i> <i>Scapania calcicolea</i> <i>Conocephalum conicum</i> <i>Pellia neesiana</i> <i>Riccia fluitans</i> <i>Ricciocarpos natans</i>	(882) (731) (78) (137) (195) (709) (194) (731) (190) (190) (974) (190) (190)	Cultured cells
2018	γ -Linolenic acid (18:3n-6) (=6,9,12-Octadecatrienoic acid)	$\text{C}_{18}\text{H}_{30}\text{O}_2$			<i>Pellia neesiana</i> <i>Riccia fluitans</i>	(190) (190)	
2019	Stearidonic acid (18:4n-3) (=6,9,12,15-Octadecatetraenoic acid)	$\text{C}_{18}\text{H}_{28}\text{O}_2$			<i>Ricciocarpos natans</i> <i>Pellia neesiana</i> <i>Riccia fluitans</i>	(974) (190) (190)	
2020	11,14-Eicosadienoic acid (20:2n-6)	$\text{C}_{20}\text{H}_{36}\text{O}_2$			<i>Pellia neesiana</i> <i>Riccia fluitans</i>	(190) (190)	
2021	5,8,11-Eicosatrienoic acid (20:3n-9)	$\text{C}_{20}\text{H}_{34}\text{O}_2$			<i>Pellia neesiana</i> <i>Riccia fluitans</i>	(190) (190)	
2022	8,11,14-Eicosatrienoic acid (20:3n-6)	$\text{C}_{20}\text{H}_{34}\text{O}_2$			<i>Pellia neesiana</i> <i>Riccia fluitans</i>	(190) (190)	
2023	Arachidonic acid (20:4n-6) (=5,8,11,14-Eicosatetraenoic acid)	$\text{C}_{20}\text{H}_{32}\text{O}_2$			<i>Conocephalum conicum</i> <i>Herbertus adancus</i> subsp. <i>hutchinsiae</i> <i>Marchantia polymorpha</i>	(731) (137) (709)	Cultured cells

2024	8,11,14,17-Eicosatetraenoic (20:4n-3)	C ₂₀ H ₃₂ O ₂	<i>Pellia neesiana</i> (190)	Cultured cells
2025	Methyl (Z)-8,11,14,17-eicosatetraenoate	C ₂₁ H ₃₄ O ₂	<i>Riccia fluitans</i> (190)	
2026	EPA (20:5n-3) (=Eicosapentaenoic acid)	C ₂₀ H ₃₀ O ₂	<i>Pellia neesiana</i> (190)	
			<i>Riccia fluitans</i> (190)	
			<i>Frullania spinifera</i> (78)	
			<i>Conocephalum conicum</i> (731)	
			<i>Herbertus aduncus</i> subsp. <i>hutchinsiae</i> (137)	
			<i>Marchantia polymorpha</i> (709)	
			<i>Pellia neesiana</i> (190)	
			<i>Riccia fluitans</i> (190)	
			<i>Pellia neesiana</i> (190)	
			<i>Riccia fluitans</i> (190)	
			<i>Pellia neesiana</i> (190)	
			<i>Riccia fluitans</i> (190)	
			<i>Pellia neesiana</i> (190)	
			<i>Riccia fluitans</i> (190)	
			<i>Monoclea forsteri</i> (635)	
			<i>Pellia neesiana</i> (190)	
			<i>Riccia fluitans</i> (190)	
			<i>Pellia neesiana</i> (190)	
			<i>Riccia fluitans</i> (190)	
			<i>Pellia neesiana</i> (190)	
			<i>Riccia fluitans</i> (190)	
			<i>Pellia neesiana</i> (190)	
			<i>Riccia fluitans</i> (190)	
			<i>Pellia neesiana</i> (190)	
			<i>Riccia fluitans</i> (190)	
2027	13,16-Docosadienoic acid (22:2n-6)	C ₂₂ H ₄₀ O ₂		
2028	13,16,19-Docosatrienoic acid (22:3n-3)	C ₂₂ H ₃₈ O ₂		
2029	10,13,16-Docosatrienoic acid (22:3n-6)	C ₂₂ H ₃₈ O ₂		
2030	10,13,16,19-Docosatetraenoic acid (22:4n-3)	C ₂₂ H ₃₆ O ₂		
2031	9-Octadecen-6-ynoic acid (6a,9-18:2)	C ₁₈ H ₃₀ O ₂		
2032	Monocleic acid (=10-Keto-(8E)-octadecen-6-ynoic acid)	C ₁₈ H ₂₈ O ₃		
2033	Creprenic acid (9,12a-18:2) (=9-Octadecen-12-ynoic acid)	C ₁₈ H ₃₀ O ₂		
2034	9,12-Octadecadien-6-ynoic acid (6a,9,12-18:3)	C ₁₈ H ₂₈ O ₂		
2035	9,12,15-Octadecatrien-6-ynoic acid (6a,9,12,15-18:4)	C ₁₈ H ₂₆ O ₂		

(continued)

Table 4.9 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/^{\circ}\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
2036	11,14-Eicosadien-8-ynoic acid (8a,11,14-20:3)	$\text{C}_{20}\text{H}_{32}\text{O}_2$			<i>Pellia neesiana</i>	(190)	
2037	8,11,14-Eicosatrien-5-ynoic acid (5a,8,11,14-20:4)	$\text{C}_{20}\text{H}_{30}\text{O}_2$			<i>Riccia fluitans</i>	(190)	
2038	Oxacycloheptadecan-2-one	$\text{C}_{16}\text{H}_{30}\text{O}_2$			<i>Pellia neesiana</i> <i>Riccia fluitans</i> <i>Marchantia polymorpha</i>	(190) (190) (492)	Sporophyte
2039	3-O-[(α -D-Galactopyranosyl (1'' $\rightarrow$ 6')- β -D- galactopyranosyl]- 1-O-[(9Z,12Z,15Z)- octadecatrienoyl] glycerol	$\text{C}_{33}\text{H}_{56}\text{O}_{14}$		+42.5	<i>Marchantia polymorpha</i>	(634)	
2040	Cycloart-24-en-3 β -yl α -linolenate	$\text{C}_{48}\text{H}_{78}\text{O}_2$			<i>Plagiochila circinalis</i>	(898)	
2041	Cycloart-24-en-3 β -yl arachidonate	$\text{C}_{50}\text{H}_{78}\text{O}_2$			<i>Plagiochila circinalis</i>	(898)	
2042	Cycloart-24-en-3 β -yl eicosapentaenoate	$\text{C}_{50}\text{H}_{78}\text{O}_2$			<i>Plagiochila circinalis</i>	(898)	
2043	Stigmasteryl γ -linolenate	$\text{C}_{50}\text{H}_{80}\text{O}_2$			<i>Plagiochila circinalis</i>	(898)	
2044	Stigmasteryl palmitate	$\text{C}_{45}\text{H}_{78}\text{O}_2$			<i>Frullania hamatiloba</i>	(316)	
2045	4 α ,14 α -Dimethyl-8,24(28)- ergostadien-3 β -yl arachidonate	$\text{C}_{50}\text{H}_{80}\text{O}_2$			<i>Plagiochasma intermedium</i> <i>Plagiochila circinalis</i>	(924) (898)	
2046	4 α ,14 α -Dimethyl-8,24(28)- ergostadien-3 β -yl eicosapentaenoate	$\text{C}_{50}\text{H}_{78}\text{O}_2$			<i>Plagiochila circinalis</i>	(898)	

Chiloscyphus ammophilus, *C. lingulatus*, *C. allodontus*, *C. coalitus*, and *C. triacanthus* elaborate various sesquiterpene hydrocarbons, with *C. pallidus* producing a very strong bug-like smell, due to the presence of a large amount of (*E*)-dec-2-enal (1944), and smaller amounts of (*Z*)-dec-2-enal (1945), (*E*)-pent-2-enal (1942), its (*Z*)-isomer (1943), and a stereoisomer (72).

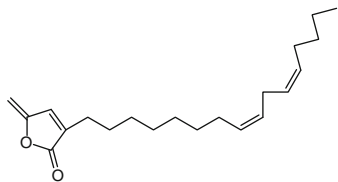
From the ether extract of *Cheilelejeunea imbricata* the strong milky smelling (*R*)-dodec-2-en-1,5-olide (1946) and (*R*)-tetradec-2-en-1,5-olide (1947) were isolated. Their physical and spectroscopic data were identical to those of these compounds when produced synthetically (275). An estimated enantio excess of more than 99% of 1946 was determined by GC/MS equipped with an enantioselective capillary column (879).

Marchantia paleacea subsp. *diptera* has been studied chemically, and marchantins A (1577) and C-G (1579–1582) have been isolated (40). A reinvestigation of the ether extract of this liverwort led to the isolation of the two new but very unstable butenolides, 1948 and 1949. Their structures were elucidated as 2-[(8'*Z*,11'*Z*)-hexadecadienyl]-penta-2,4-dien-1,4-olide (1948) and 2-[(8'*Z*)-hexadecenyl]-penta-2,4-dien-1,4-olide (1949) by analysis of their UV (262 nm) and IR spectra (1775 cm^{-1}) as well as ^1H - ^1H spin decoupling and COSY, HMQC, and HMBC NMR methods (877).

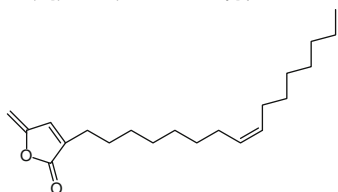
The *n*-hexane extract of *Marchantia emarginata* subsp. *tosana* was fractionated over silica gel to give the two new butenolides, 1950 and 1951, together with 2-[(8'*Z*,11'*Z*)-hexadecadienyl]-penta-2,4-dien-1,4-olide (1948). Compound 1950 was also isolated from the ether extract of the New Zealand *M. foliacea*. The ^1H and ^{13}C NMR data of 1950 resembled those of 1948 isolated from *M. paleacea* var. *diptera*, indicating that 1950 might be the side chain isomer of 1948. The positions of the three double bonds in the side chain were confirmed by comparison of the ^1H NMR spectrum with that of linolenic acid (2017). Thus, the structure of 1950 was assigned as 2-[(7'*Z*,10'*Z*,13'*Z*)-hexadecatrienyl]-penta-2,4-dien-1,4-olide. The ^1H and ^{13}C NMR spectra of 1951 were similar to those of 1950, except for the lactone ring, indicating that 1951 is based on the same skeleton as 1950 and 1948. The configuration of the hydroxy group at C-4 was confirmed by the presence of an NOE correlation between the H-3 and H-4 protons. Thus, the structure of 1951 was established as 2 β -[(7'*Z*,10'*Z*,13'*Z*)-hexadecatrienyl]-3 β -hydroxypenta-2,4-dien-1,4-olide (347). *Marchantia paleacea* collected in Indonesia elaborates β -*n*-octyl- γ -butanolide (1951a) (424). These are the first examples of the isolation of butenolides possessing a long-chain alkyl group from the liverworts, although the very similar butenolides 1951b and 1951c were isolated from the marine gorgonians *Plexaura flava* (673) and *Euplexaura flava* (408).

The presence of *n*-heptanal (1952) and *n*-nonanal (1953) was shown in essential oils obtained from Portuguese liverworts in the genera *Asterella* and *Radula* by GC/MS (222, 223). This same technique was used to identify octan-3-one (1954) in *Marsupella emarginata* (17). 2-Undecanone (1955), 2-tridecanone (1956), 2-pentadecanone (1959), and 1-tetradecanol (1958) were identified in a crude

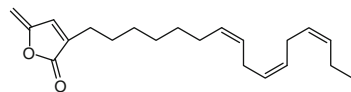
extract of *Frullania solanderiana*, using again GC/MS (78). Compound **1955** was also detected in the Colombian *Adelanthus decipiens* (695), *Asterella africana* (222), and *Plagiochila bifaria* (333). The Greek *Fossombronia angulosa* also elaborates 2-tridecanone (1956) (492).



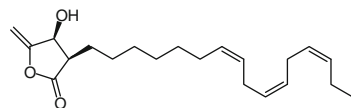
1948 (2-[(8'Z,11'Z)-hexadecadienyl]-penta-2,4-dien-1,4-olide)



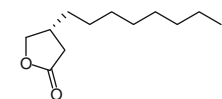
1949 (2-[(8'Z)-hexadecenyl]-penta-2,4-dien-1,4-olide)



1950 (2-[(7'Z,10'Z,13'Z)-hexadecatrienyl]-penta-2,4-dien-1,4-olide)

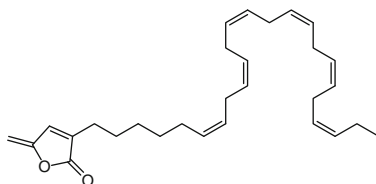


1951 (2β-[(7'Z,10'Z,13'Z)-hexadecatrienyl]-3β-hydroxypent-4-en-1,4-olide)

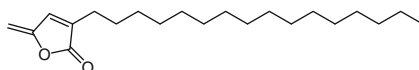


1951a (β-n-octyl-γ-butanolide)

Acetogenins found in the Marchantiophyta

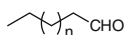


1951b (2-[(6'Z,9'Z,12'Z,15'Z,18'Z,21'Z)-tetraosa-hexaenyl]-penta-2,4-dien-1,4-olide)



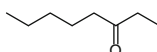
1951c (2-hexadecyl-penta-2,4-dien-1,4-olide)

Acetogenins found in marine gorgonians

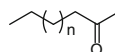


1952 $n=4$ (*n*-heptanal)

1953 $n=6$ (*n*-nonanal)



1954 (octan-3-one)



1955 $n=6$ (2-undecanone)

1956 $n=8$ (2-tridecanone)

1959 $n=10$ (2-pentadecanone)



1957 $n=10$ (tetradecane)

1960 $n=12$ (hexadecane)

1962 $n=13$ (heptadecane)

1963 $n=14$ (octadecane)

1968 $n=15$ (nonadecane)

1969 $n=16$ (eicosane)

1970 $n=17$ (heneicosane)

1971 $n=18$ (docosane)

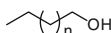
1973 $n=19$ (tricosane)

1974 $n=20$ (tetracosane)

1975 $n=21$ (pentacosane)

1976 $n=23$ (heptacosane)

1977 $n=25$ (nonacosane)



1958 $n=11$ (1-tetradecanol)

1964 $n=15$ (1-octadecanol)



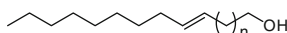
1961 $n=13$ (1-heptadecene)



1965 $n=13$ (16-octadecenal)



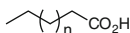
1966 $n=13$ (17-octadecenal)



1967 $n=7$ (elaidic alcohol
= 9-octadecen-1-ol)



1972 $n=18$ (1-docosene)



1978 $n=8$ (dodecanoic acid)

1979 $n=9$ (tridecanoic acid)

1980 $n=10$ (tetradecanoic acid)

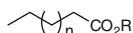
1981 $n=11$ (pentadecanoic acid)

1982 $n=12$ (hexadecanoic acid)

1986 $n=13$ (heptadecanoic acid)

1988 $n=14$ (octadecanoic acid)

1992 $n=16$ (eicosanoic acid)



1983 $n=12$, R=Me (methyl palmitate)

1984 $n=12$, R=Et (ethyl palmitate)

1985 $n=12$, R=Bu (butyl palmitate)

1987 $n=13$, R=Bu (butyl heptadecanoate)

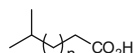
1990 $n=14$, R=Me (methyl octadecanoate)

1991 $n=14$, R=Bu (butyl octadecanoate)

1993 $n=18$, R=Me (methyl docosanoate)

1994 $n=20$, R=Me (methyl tetracosanoate)

1995 $n=22$, R=Me (methyl hexacosanoate)



1989 $n=13$ (isostearic acid)

Lipids found in the Marchantiophyta

The presence of various *n*-alkanes, *i.e.* tetra- (**1957**), hexa- (**1960**), hepta- (**1962**), octa- (**1963**), and nonadecanes (**1968**), and eicosane (**1969**), heneicosane (**1970**), and doco- (**1971**), trico- (**1973**), tetraco- (**1974**), pentaco- (**1975**), heptaco- (**1976**), and nonacosanes (**1977**), was confirmed in *Metzgeria*, *Lepidozia*

Frullania, and *Scapania* species, as shown in Table 4.9. The *n*-alkenes, 1-heptadecene (1961) and 1-docosene (1972), were found in *Frullania chevalierii* and *F. scandens*, respectively (78). The latter species also contained 16-octadecenal (1965) and 17-octadecanal (1966) (78). All these components were detected by GC/MS.

The free odd-carbon number carboxylic acids, tridecanoic acid (1979) and pentadecanoic acid (1981), were detected in *Frullania pycnantha* (78) and in *Plagiochila tabinensis*, respectively (331). Palmitic acid (1982) and ethyl palmitate (1984) were identified in the Taiwanese *Plagiochila elegans* (470).

Dixit and coworkers investigated the distribution of lipids in *Scapania calcicolea* (194). Methyl hexadecanoate (1983), octadecanoate (1990), docosanoate (1993), tetracosanoate (1994), 9-octadecenoate (2003), and butyl hexadecanoate (1985) and octadecanoate (1991), along with the free acids hexadecanoic (1982), octadecanoic (1988), and octadecatrienoic acids (2017) and the *n*-alkanes heptadecane (1962) and heptacosane (1976), were identified by GC/MS. The same authors analyzed lipids of the ether extract of *Lepidozia reptans* by GC/MS to detect the *n*-alkanes heptadecane (1962), octadecane (1963), and nonadecane (1968), methyl hexadecanoate (1983) and docosanoate (1993), butyl hexadecanoate (1985), heptadecanoate (1987), and octadecanoate (1991), hexadecanoic acid (1982), and octadecanoic acid (1988), and the acyclic alcohol, elaidic alcohol (= 9-octadecen-1-ol) (1967) (195).

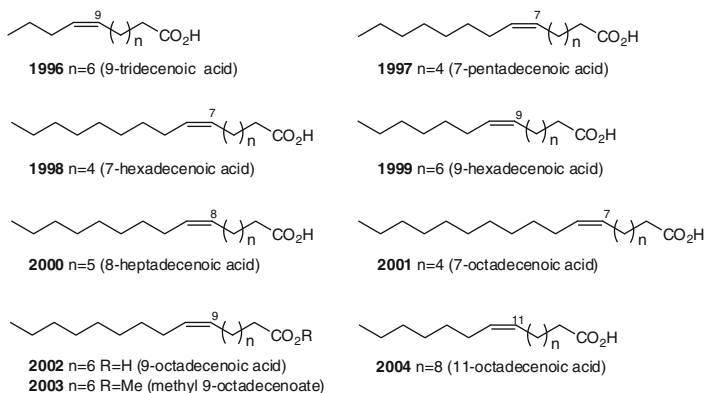
The ether extract of the New Zealand *Isotachis lyallii* was fractionated by column chromatography to give the alkanoyl alkanoates $C_mH_{2m} + 1COOC_nH_{2n} + 1$ ($m = 16, 18, 22$; $n = 20, 22$) (73).

The NMR spectrum of the ester fraction of *Plagiochila tabinensis* clearly showed resonances for triacylglycerols and steryl esters in the ratio of 1:3. Methanolysis of this fraction yielded a mixture of fatty acid methyl esters with the major components, hexadecanoic (1982) and octadecanoic acids (1988), being detected as the corresponding methyl esters. In addition, two further major sterols, campesterol (1420) and stigmasterol (1421), were detected by GC/MS analysis (331).

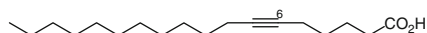
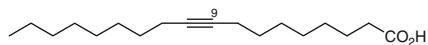
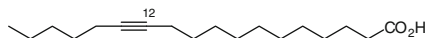
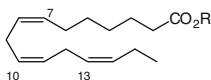
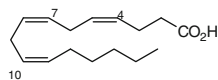
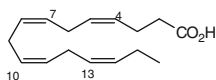
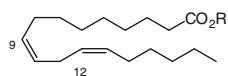
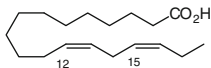
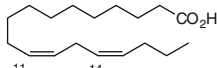
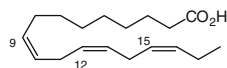
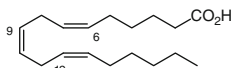
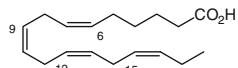
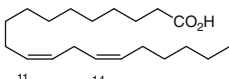
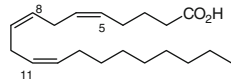
Hexadecanoic (1982), octadecanoic (1988), eicosanoic (1992), docosanoic (1993), tetracosanoic (1994), and hexacosanoic acids (1995) were analyzed in the $CDCl_3$ extract of *Plagiochila atlantica* as their methyl esters by GC/MS. Among these, octadecanoic acid (1988) (61%) was the predominant component. These results differed from those obtained from *P. tabinensis*, for which steryl esters were more abundant than triglycerides and the major components of the free acid and steroid fractions of the surface wax were found to contain hexadecanoyl moieties (334).

Riccia fluitans and *Pellia neesiana* were analyzed for the fatty acid composition of their total lipids, triacylglycerols, and diacylglyceryltrimethylhomoserine and phospholipid constituents (190). The saturated fatty acids in these species were determined in turn as 13.3% and 22.7% as total lipids and 13.6% and 17.4%

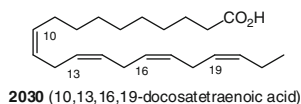
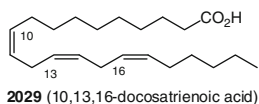
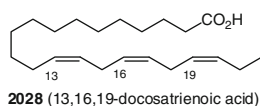
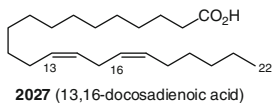
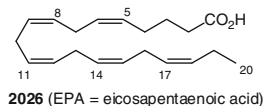
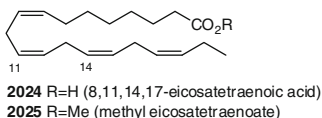
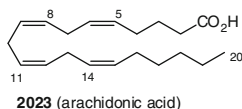
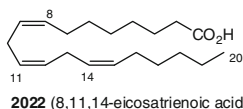
as triglycerols. The fatty acids identified were the ubiquitous plant acids dodecanoic (**1978**), tetradecanoic (**1980**), pentadecanoic (**1981**), hexadecanoic (**1982**), heptadecanoic (**1986**), octadecanoic (**1988**), and eicosanoic acids (**1992**). The presence of the monoenoic acids **1996–1998**, **2000**, **2001**, and **2004** in both species as total lipids and as triglycerols was 3–10% higher than the saturated fatty acids. The distribution of the monoacetylenic acids **2031**, **2032**, and **2033** was also determined, with the monoene in both species being 3.5 and 1.2% as total lipids and 15.1 and 13.9% as triglycerols. In the case of the polyenoic acid composition (**2008–2011**, **2015**, **2018–2030**), *R. fluitans* and *P. neesiana* contained 63.5 and 50.6% as the total lipids and 69.8 and 56.2% as triglycerides, respectively. Both species elaborated total fatty acids and triglycerols containing high amounts of the monoacetylenic acids **2005–2007**, acetylenic acids (**2034–2037**) with a polyene unit, and fatty acids with triene (**2008–2010**) and tetraene (**2011**) moieties. In the case of the triglycerols, *P. fluitans* was found to produce 80.2% of polyene-yne acids, with smaller amounts (57.3%) of such acids detected in *P. neesiana*. γ -Linolenic acid (6,9,12-octadecatrienoic acid) (**2018**) was the most abundant fatty acid among the total lipids and triglycerols in both species. *R. fluitans* also produced diacylglycerotrimethylhomoserine (34.3%), phosphatidylcholine (21.9%), phosphatidylglycerol (17.3%), phosphatidylethanolamine (10.6%), phosphatidylseline (10.3%), and phosphatidylinositol (4.1%). *P. neesiana* contained almost the same amount of these substances as found in *R. fluitans* (**190**).



Fatty acids found in the Marchantiophyta

**2005** (tariric acid = 6-octadecynoic acid)**2006** (stearolic acid = 9-octadecynoic acid)**2007** (12-octadecynoic acid)**2008** R=H (7,10,13-hexadecatrienoic acid)**2009** R=Me (methyl 7,10,13-hexadecatrienoate)**2010** (4,7,10-hexadecatrienoic acid)**2011** (4,7,10,13-hexadecatetraenoic acid)**2012** R=H (linoleic acid)**2013** R=Me (methyl linoleate)**2014** R=Et (ethyl linoleate)**2015** (12,15-octadecadienoic acid)**2016** (11,14-octadecadienoic acid)**2017** (α-linolenic acid)**2018** (γ-linolenic acid)**2019** (stearidonic acid)**2020** (11,14-eicosadienoic acid)**2021** (5,8,11-eicosatrienoic acid)

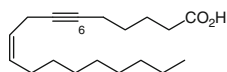
Unsaturated fatty acids found in the Marchantiophyta



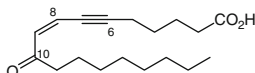
Unsaturated fatty acids found in the Marchantiophyta

The ether extract of the sporophytes of *Pellia epiphylla* was purified by column chromatography to give palmitic acid (**1982**), methyl linoleate (**2013**), and methyl 7,10,13-hexadecatrienoate (**2009**) ([175](#)). The same fatty acids have been found in the liverworts *Pellia endiviifolia* and *Conocephalum conicum* ([39](#)). The ether extract of the sporophytes of *Pellia epiphylla* was purified by column chromatography to give 1-octadecanol (**1964**), which also occurred in the dichloromethane extract of the spores of *P. epiphylla* ([175](#)). Palmitic (**1982**), isostearic (**1989**), linoleic (**2012**), α -linolenic (**2017**), arachidonic (**2023**), and eicosa-(5Z,8Z, 11Z,14Z,17Z)-pentaenoic acids (**2026**) were found in *Herbertus adancus* subsp. *hutchinsiae* ([137](#)). The ether extract of *Chandonanthus hirtellus* collected in Tahiti was analyzed by GC/MS to detect ethyl linoleate (**2014**) ([423](#)). The fatty acid composition was analyzed in suspension cultured cells of *Marchantia polymorpha* grown at both 25 and 15°C ([709](#)). Cells grown at the former temperature contained about 18% linolenic, 11.5% arachidonic, and 3% eicosapentaenoic acids, as percentages of the total fatty acids. When cells were grown at 15°C, the relative proportions of linolenic and eicosapentaenoic acids showed large increases. The levels of arachidonic (**2023**) and eicosapentaenoic (**2026**) acids were increased in the chloroplast fraction but not in the extra-chloroplast fraction. On the other hand, linolenic acid was increased in both fractions. Galactolipids were present in the chloroplasts, phosphatidylethanolamine in the extra-chloroplast fraction, and phosphatidylcholine, phosphatidylglycerol, phosphatidylinositol, and diacylglycerol in both compartments. Of the lipid series bound to eicosapentaenoic acid, only monogalactosyl diacylglycerol and

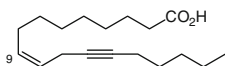
chloroplatic phosphatidylcholine were increased at the lower temperature. In liverwort cells, eicosapentaenoic acid (**2026**) plays a specific role at low temperature.



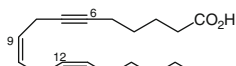
2031 (9-octadecen-6-ynoic acid)



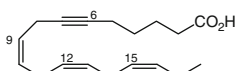
2032 (monocleic acid (= 10-keto-(8*E*)-octadecen-6-ynoic acid))



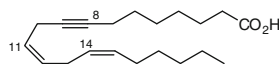
2033 (crepenynic acid
(= 9-octadecen-12-ynoic acid))



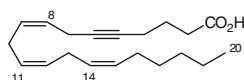
2034 (9,12-octadecadien-6-ynoic acid)



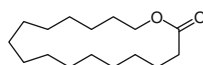
2035 (9,12,15-octadecatrien-6-ynoic acid)



2036 (11,14-eicosadien-8-ynoic acid)



2037 (8,11,14-eicosatrien-5-ynoic acid)

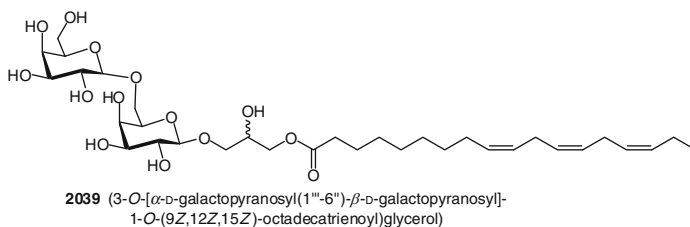


2038 (oxacycloheptadecan-2-one)

Unsaturated fatty acids and macrocyclic lactone found in the Marchantiophyta

Ludwiczuk and colleagues detected oxacycloheptadecan-2-one (**2038**) in a crude extract of the sporophytes of *Marchantia polymorpha* by GC/MS analysis ([492](#)). Fractionation of the methanol extract of *Marchantia polymorpha* resulted in the isolation of the new acyl digalactosylglycerol **2039**. Hydrolysis of **2039** gave glycerol, D-galactose, and linolenic acid. Acetylation of **2039** gave an octaacetate for which the HR-FAB-MS and ^{13}C - and ^1H NMR spectra indicated the presence of two galactopyranose moieties. The complete structure in the form of an octaacetate was established as 3-*O*-[α -D-galactopyranosyl(1''' $\rightarrow$ 6'')- β -D-galactopyranosyl]-1-*O*-[(9*Z*,12*Z*,15*Z*)-octadecatrienoyl]glycerol octaacetate, by detailed analysis of the NMR spectra inclusive of a HMBC experiment. Thus, this natural product was determined to be 3-*O*-[α -D-galactopyranosyl(1''' $\rightarrow$ 6'')- β -D-galactopyranosyl]-1-*O*-[(9*Z*,12*Z*,15*Z*)-octadecatrienoyl]glycerol (**2039**) ([634](#)). 1-*O*- β -D-(6'-Caffeoyl) glucopyranosyl glycerol and its analogues have been isolated from the European liverwort *Frullania muscicola* ([442](#)). Similar (2*S*)-1-*O*-[(7*Z*,10*Z*,13*Z*)-hexadecatrienoyl]-3-*O*- β -galactopyranosylglycerol and (2*S*)-1-*O*-[(9*Z*,12*Z*)-octadecadienoyl]-3-*O*- β -galactopyranosylglycerol monogalactosides of **2039** have been isolated from the higher plant, *Hydrocotyle ramiflora* (Umbelliferae) ([456](#)). This represented the first isolation of a digalactopyranosymonglycerol from the Marchantiophyta,

although such compounds been found in the leaves of higher plants, ferns, mosses, and seaweeds (420).

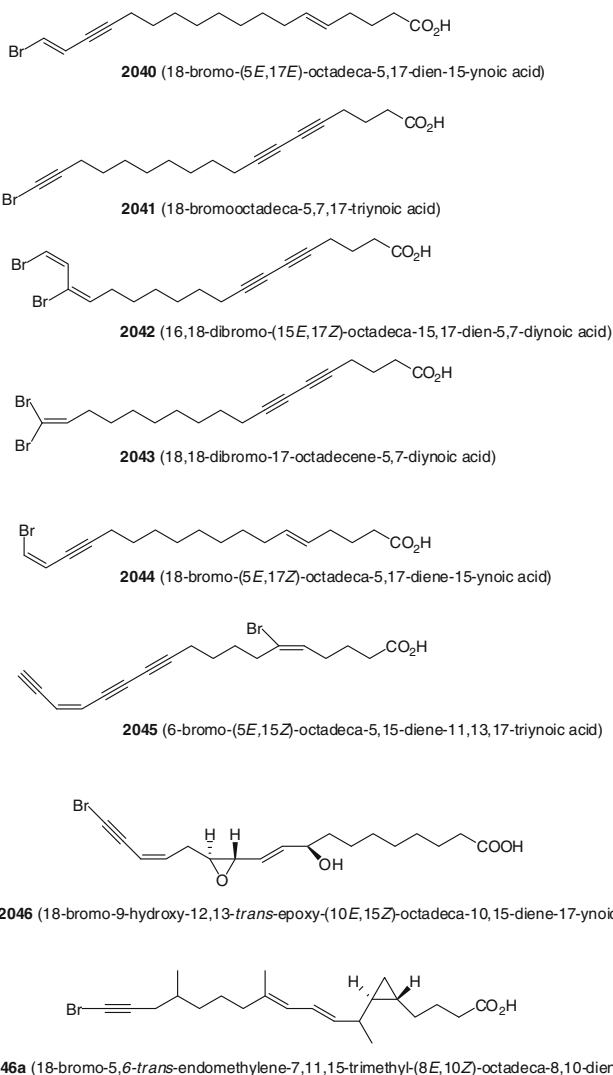


Acyl glycosyl glycerol derivative found in the Marchantiophyta

18-Bromo-(5*E*,17*E*)-octadeca-5,17-diene-15-ynoic (**2040**), 18-bromo-octaeca-5,7,17-triynoic (**2041**), 16,18-dibromo-(5*E*,17*Z*)-octadeca-15,17-diene-5,7-diynoic (**2042**), 18,18-dibromo-17-octadecene-5,7-diynoic (**2043**), 18-bromo-(15*E*,17*Z*)-octadeca-5,7-diene-15-ynoic (**2044**), 6-bromo-(5*E*,15*Z*)-octadeca-5,15-diene-11,13,17-triynoic (**2045**), 18-bromo-9-hydroxy-12,13-*trans*-epoxy-(10*E*,15*Z*)-octadeca-10,15-diene-17-ynoic (**2046**), and 18-bromo-5,6-*trans*-endomethylene-7,22,15-trimethyl-(8*E*,10*Z*)-octadeca-8,10-diene-17-ynic acids (**2046a**) were isolated from eight lichens (Fig. 4.27) including *Cladonia furcata*, *Lecanora fructulosa*, and *Leptogium saturninum* collected in the Central Asia (677). However, such brominated compounds have not yet been found in any liverworts although chlorinated sesquiterpenes and aromatic compounds have been isolated from certain liverworts, as mentioned earlier.



Fig. 4.27 Lichen (*Rimelia* sp.)



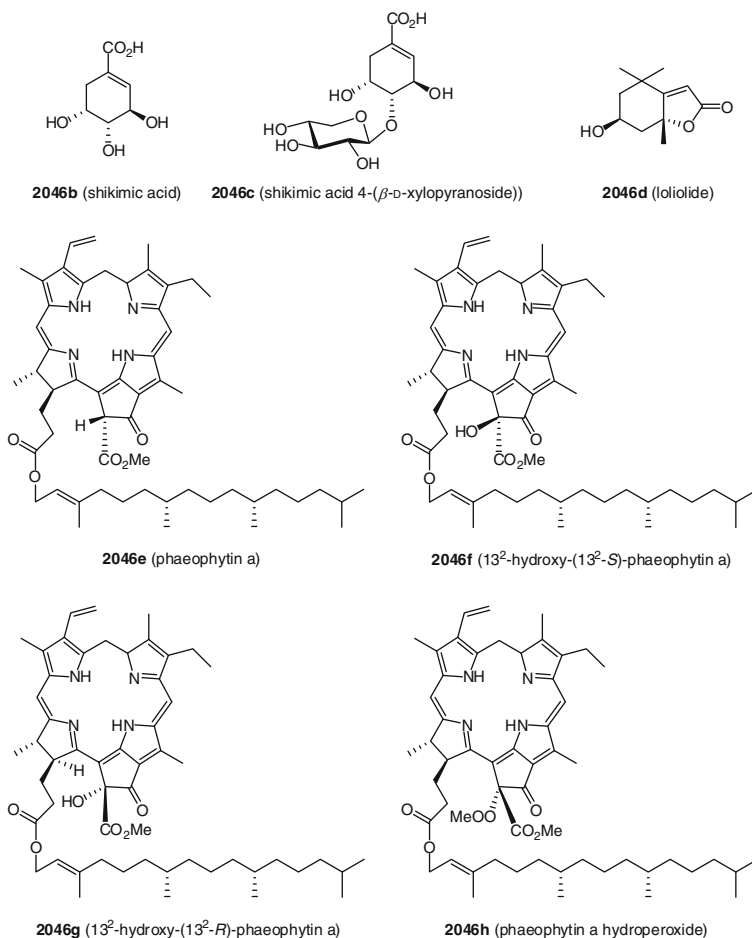
Brominated fatty acids found in lichens

4.8 Miscellaneous

Cell cultures of *Marchantia polymorpha* have the ability to hydrolyze acetates to the corresponding alcohols. An esterase in the cultured suspension cells of *M. polymorpha* is secreted into the culture medium. The esterase was partially purified. It was

confirmed that the enzyme is a single polypeptide with $M_r = 40$ kD on a molecular sieve column and upon SDS-polyacrylamide gel electrophoresis (369).

The methanol extract of *Blasia pusilla* contained not only bisbibenzyls and their dimers but also shikimic acid (**2046b**) as the major component and apigenin-7-*O*- β -D-glucoside (**1915**) (971). Shikimic acid 4-(β -D-xylopyranoside) (**2046c**) has been isolated from *Marchantia polymorpha* (667) (see Table 4.10).



Miscellaneous compounds found in the Marchantiophyta

The ether extract of the European *Pellia epiphylla* was purified by column chromatography and HPLC to yield the carotenoid derivative, lolilide (**2046c**), which was isolated first time from a liverwort (176).

Phaeophytin a (**2046e**), 13^2 -hydroxy-(13^2 -R)-phaeophytin a (**2046f**), 13^2 -hydroxy-(13^2 -S)-phaeophytin a (**2046g**), and 13^2 -(MeOO)-(13^2 -R)-phaeophytin a (= phaeophytin a methylperoxide) (**2046h**) were isolated from a methanol extract

Table 4.10 Miscellaneous constituents found in the Marchantiophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D / ^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$	Plant source(s)	Reference(s)	Comments
2046b	Shikimic acid	$\text{C}_7\text{H}_{10}\text{O}_5$	152-153		<i>Blasia postilla</i>	(971)	
2046c	Shikimic acid 4-(β -D-xylopyranoside)	$\text{C}_{12}\text{H}_{18}\text{O}_9$		-255	<i>Marchantia polymorpha</i>	(667)	
2046d	Loliolide	$\text{C}_{11}\text{H}_{16}\text{O}_3$			<i>Pellia epiphylla</i>	(176)	
2046e	Phaeophytin a	$\text{C}_{55}\text{H}_{74}\text{N}_4\text{O}_5$			<i>Plagiochila ovalifolia</i>	(529)	Cell culture
2046f	13 ² -Hydroxy-(13 ² -S)-phaeophytin a	$\text{C}_{55}\text{H}_{74}\text{N}_4\text{O}_6$			<i>Plagiochila ovalifolia</i>	(529)	Cell culture
2046g	13 ² -Hydroxy-(13 ² -R)-phaeophytin a	$\text{C}_{55}\text{H}_{74}\text{N}_4\text{O}_6$			<i>Plagiochila ovalifolia</i>	(529)	Cell culture
2046h	Phaeophytin a hydroperoxide	$\text{C}_{56}\text{H}_{77}\text{N}_4\text{O}_7$			<i>Plagiochila ovalifolia</i>	(529)	Cell culture

of the cell suspension culture of the liverwort *Plagiochila ovalifolia*. Compounds **2046e–2046h** have been found in *Megaceros flagellaris* (529). All these substances have been found also in the moss, *Entodon rubicundus* (40). Such compounds are often artefacts derived from chlorophyll a from the phytochemical work-up procedures used.

5 Chemical Constituents of Bryophyta

More than 14,000 species belonging to the Bryophyta (mosses) are known, but, only a small percentage of these taxa have been analyzed chemically (40). In particular, the distribution of flavonoids in the Bryophyta has been studied by a German group (250). The distribution of terpenoids, simple benzoic, cinnamic, and phthalic acid derivatives, coumarins, and some nitrogen-containing aromatic compounds, the benzonaphthoxanthenones, has been investigated from several species of the Bryophyta. One of the most interesting recent discoveries concerning the chemical constituents of the Bryophyta is that *Plagiomnium acutum* (Mniaceae), belonging to the Eubryales, produces enantiomers of sesqui- and diterpenoids of those found in higher plants (884).

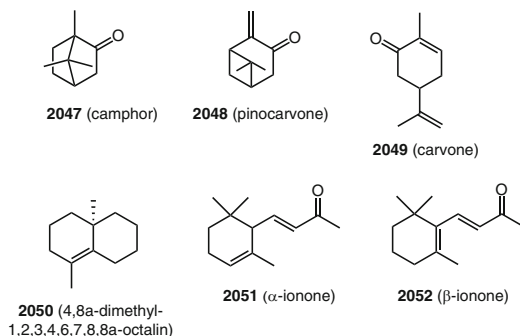
5.1 Terpenoids

More than 800 terpenoids, excluding triterpenoids and tetraterpenoids, and 300 aromatic compounds, not including flavonoids, have been isolated from or detected in the Marchantiophyta (39, 40). Only four monoterpene hydrocarbons, α -phellandrene (26), β -phellandrene (27), Δ^3 -carene (40), and α -pinene (47) have been detected in *Sphagnum* species belonging to the Bryophyta. No sesquiterpenoids have been isolated from or detected in this class. Only four diterpenoids, *ent*-16 β -hydroxykaurane (1154), momilactones A (2064) and B (2065), and chamaecydin have been found in the Bryophyta, although 14,000 species belonging to the Bryophyta have been recorded (40). Since 1995, 18 monoterpenoids, five trinorsesquiterpenoids, 72 sesquiterpenoids, ten diterpenoids, and nine triterpenoids have been isolated from or detected in the Bryophyta.

5.1.1 Monoterpenoids

The essential oils obtained by hydrodistillation from seven European mosses, *Homalia trichomanoides* (Neckeraceae), *Mnium hornum*, *Mnium marginatum*, *Mnium stellare* (Mniaceae), *Plagiomnium undulatum* (Mniaceae), *Plagiothecium undulatum* (Plagiotheciaceae), and *Taxiphyllum wisgrillii* (Hypnaceae) were analyzed by GC/MS (708).

As shown in Table 5.1, *H. trichomanoides*, *M. marginatum*, *Plagiomnium undulatum*, and *Plagiothecium undulatum* elaborate various types of monoterpenoids, among which cyclocitral (**12**) is a very common component in these mosses. Furthermore, the monoterpene hydrocarbons myrcene (**1**), limonene, (**19**) α -pinene (**47**), β -pinene (**48**), and camphene (**55**) as well as the oxygenated monoterpenoids, terpinen-4-ol (**16**), α -terpineol (**17**), α -terpinyl acetate (**18**), borneol (**57**), bornyl acetate (**58**), and camphor (**2047**) were detected as frequent constituents. Δ^3 -Carene (**40**) was found in *Plagiomnium undulatum* and *Plagiothecium undulatum*, *trans*-pinocarveol (**49**) in *H. trichomanoides*, pinocarvone (**2048**), myrtenal (**50**) and carvone (**2049**) in *Plagiothecium undulatum*, and myrtenol (**51**) in *H. trichomanoides*. Except for the presence of camphor, pinocarvone, and carvone, all of the detected monoterpenoids in these seven mosses have been identified before in the Marchantiophyta, as mentioned previously.



Monoterpenoids and trinosesquiterpenoids found in the Bryophyta

Table 5.1 Monoterpenoids found in the Bryophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/^{\circ}\text{cm}^2\text{ g}^{-1}10^{-1}$	Plant source(s)	Reference(s)	Comments
1	β -Myrcene	$\text{C}_{10}\text{H}_{16}$			<i>Plagiothecium undulatum</i>	(708)	GC-MS
12	β -Cyclocitral	$\text{C}_{10}\text{H}_{16}\text{O}$			<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium hornum</i>	(708)	
					<i>Mnium stellare</i>	(708)	
					<i>Plagiommium undulatum</i>	(708)	
					<i>Plagiothecium undulatum</i>	(708)	
					<i>Taxiphyllum wisgrillii</i>	(708)	
16	Terpinene-4-ol	$\text{C}_{10}\text{H}_{18}\text{O}$			<i>Homalia trichomanoides</i>	(708)	
17	α -Terpineol	$\text{C}_{10}\text{H}_{18}\text{O}$			<i>Taxiphyllum wisgrillii</i>	(708)	
18	α -Terpinyl acetate	$\text{C}_{12}\text{H}_{20}\text{O}_2$			<i>Mnium hornum</i>	(708)	
					<i>Plagiommium undulatum</i>	(708)	
19	Limonene	$\text{C}_{10}\text{H}_{16}$			<i>Plagiothecium undulatum</i>	(708)	
					<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium hornum</i>	(708)	
					<i>Mnium marginatum</i>	(708)	
					<i>Plagiommium undulatum</i>	(708)	
40	Δ^3 -Carene	$\text{C}_{10}\text{H}_{16}$			<i>Plagiothecium undulatum</i>	(708)	
					<i>Plagiommium undulatum</i>	(708)	
					<i>Plagiothecium undulatum</i>	(708)	
47	α -Pinene	$\text{C}_{10}\text{H}_{16}$			<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium hornum</i>	(708)	
					<i>Mnium marginatum</i>	(708)	
					<i>Plagiommium undulatum</i>	(708)	
					<i>Plagiothecium undulatum</i>	(708)	

(continued)

Table 5.1 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
48	β -Pinene	C ₁₀ H ₁₆			<i>Homalia trichomanoides</i> <i>Plagiominium undulatum</i> <i>Plagiothecium undulatum</i> <i>Taxiphyllum wisgrillii</i>	(708) (708) (708) (708)	
49	<i>trans</i> -Pinocarveol	C ₁₀ H ₁₆ O			<i>Homalia trichomanoides</i> <i>Plagiothecium undulatum</i>	(708) (708)	
50	Myrtenal	C ₁₀ H ₁₄ O			<i>Plagiothecium undulatum</i>	(708)	
51	Myrtenol	C ₁₀ H ₁₆ O			<i>Homalia trichomanoides</i>	(708)	
55	Camphene	C ₁₀ H ₁₆			<i>Homalia trichomanoides</i> <i>Mnium hornum</i> <i>Mnium marginatum</i> <i>Plagiominium undulatum</i> <i>Plagiothecium undulatum</i>	(708) (708) (708) (708) (708)	
57	Borneol	C ₁₀ H ₁₈ O			<i>Homalia trichomanoides</i> <i>Plagiominium undulatum</i>	(708) (708)	
58	Bornyl acetate	C ₁₂ H ₂₀ O ₂			<i>Homalia trichomanoides</i> <i>Mnium hornum</i> <i>Mnium marginatum</i> <i>Plagiominium undulatum</i> <i>Plagiothecium undulatum</i>	(708) (708) (708) (708) (708)	
2047	Camphor	C ₁₀ H ₁₆ O			<i>Homalia trichomanoides</i> <i>Mnium hornum</i> <i>Plagiothecium undulatum</i>	(708) (708) (708)	
2048	Pinocarvone	C ₁₀ H ₁₄ O			<i>Plagiothecium undulatum</i>	(708)	
2049	Carvone	C ₁₀ H ₁₄ O			<i>Plagiothecium undulatum</i> <i>Plagiothecium undulatum</i>	(708) (708)	

5.1.2 Trinorsesquiterpenoids

The essential oil of *Plagiothecium undulatum* was analyzed by GC/MS to detect 4,8a-dimethyl-1,2,3,4,6,7,8,8a-octalin (**2050**) and its epoxide, (+)-(4S,4aS,5R,8aS)-4a,5-epoxydecalin (**925**) (Table 5.2). The latter compound was also identified in the essential oil of *Mnium hornum*. *Homalia trichomanioides*, *M. hornum*, *Mnium marginatum*, and *Plagiomnium undulatum* were found to contain geosmin (**925j**), which might be produced by symbiotic *Streptomyces* species (**708**).

α -Ionone (**2051**) was detected in the essential oil of *H. trichomanioides* while β -ionone (**2052**) was identified in *Plagiomnium undulatum* and *P. undulatum* (**708**).

5.1.3 Sesquiterpenoids

Toyota *et al.* (**884**) analyzed the ether extract of the Japanese *Plagiomnium acutum* by GC/MS to indicate the presence of α -acoradiene (**68**), α -cedrene (**430**), and β -cedrene (**432**). Further fractionation of the extract led to the isolation of β -cedrene (**432**), for which the specific optical rotation showed $[\alpha]_D -10.9^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$ (**884**), while that of commercially available β -cedrene (**432**) shows a positive sign ($[\alpha]_D +9.7^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$) (**6**). When both (+)- α - (**432**) and (–)- β -cedrene (**432**) were co-injected into a enantioselective capillary column, two well-separated peaks appeared in the total ion chromatogram. Thus, it is clear that β -cedrene (**432**) isolated from this moss is the enantiomer of that obtained from the higher plant-derived commercial oil (**884**). Compounds **68** and **430** might be the same enantiomers as those found in higher plants, since *ent*- β -cedrene may coexist in the same species. This was the first isolation and identification of an *ent*-sesquiterpenoid from the Bryophyta and the first record of *ent*- β -cedrene in the plant kingdom.

Subsequently, Suire (**784**) and Saritas (**708**) studied the volatile components of the ether extracts of 13 mosses and the essential oils obtained from seven mosses by means of GC/MS. β -Cedrene (**432**) and α -cedrene (**430**) were also detected in *Mnium marginatum* and *Plagiomnium undulatum*, and *Homalia trichomanioides*, *Mnium hornum* and *Plagiothecium undulatum*, respectively (**708**). *H. trichomanioides*, *M. hornum*, *M. marginatum*, *Plagiomnium undulatum*, and *Plagiothecium undulatum* elaborate a number of sesquiterpenoids, as shown in Table 5.3. Among the sesquiterpenoids identified, β -barbatene (**235**) was detected in six mosses. A rare sesquiterpene, peculiaroxide (**550**), which has been isolated from the Taiwanese liverwort, *Plagiochila peculiaris* (**953**), was also detected in *H. trichomanioides* (**708**). Except for the presence of (–)-amorpha-4,11-diene (**2053**), 1-*epi*- α -pinguisene (**2054**), *epi*- β -santalene (**2055**), 10-*epi*-muurola-4,11-diene (**2056**), α -cuprenene (**466**), α -cadinene (**2057**), zonarene (**2058**), mintsulfide (**2059**), 1,2-dihydro- α -cuparenone (**2060**), fukinanolide (**2061**), and the three newly isolated compounds, (+)-10-*epi*-muurola-4,11-diene (**2056**), (–)-1,2-dihydro- α -cuparenone (**2060**), and (+)-dauca-8,11-diene (**2062**), all of the sesquiterpenes identified in these seven mosses have been isolated from or identified in the Marchantiophyta,

Table 5.2 Trinorsesquiterpenoids found in the Bryophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
925	(+)-(4 <i>S</i> ,4 <i>aS</i> ,5 <i>R</i> ,8 <i>aS</i>)-4 <i>a</i> ,5- Epoxydecalin	C ₁₂ H ₂₀ O			<i>Mnium hornum</i> <i>Plagiommium undulatum</i>	(708) (708)	
925j	Geosmin	C ₁₂ H ₂₂ O			<i>Homalia trichomanoides</i> <i>Mnium hornum</i> <i>Mnium marginatum</i> <i>Plagiommium undulatum</i>	(708) (708) (708) (708)	
2050	4,8 <i>a</i> -Dimethyl-1,2,3,4,6,7,8,8 <i>a</i> - octalin	C ₁₂ H ₂₀			<i>Plagiommium undulatum</i>	(708)	
2051	α-Ionone	C ₁₃ H ₂₀ O			<i>Homalia trichomanoides</i>	(708)	
2052	β-Ionone	C ₁₃ H ₂₀ O			<i>Homalia trichomanoides</i> <i>Plagiommium undulatum</i> <i>Plagiothecium undulatum</i>	(708) (708) (708)	

Table 5.3 Sesquiterpenoids found in the Bryophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
68	α -Acoradiene	C ₁₅ H ₂₄			<i>Plagiomnium acutum</i>	(884)	
69	β -Acoradiene	C ₁₅ H ₂₄			<i>Homalia hornum</i>	(784)	
					<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium marginatum</i>	(708)	
					<i>Mnium stellare</i>	(708)	
					<i>Taxiphyllum wisgrillii</i>	(708)	
108	Aristolene	C ₁₅ H ₂₄			<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium marginatum</i>	(708)	
122	Anastreptene	C ₁₅ H ₂₂			<i>Mnium hornum</i>	(708)	
					<i>Mnium marginatum</i>	(708)	
134	Palustrol	C ₁₅ H ₂₆ O			<i>Mnium marginatum</i>	(708)	
156	Aromadendrene	C ₁₅ H ₂₄			<i>Homalia trichomanoides</i>	(708)	
234	α -Barbatene	C ₁₅ H ₂₄			<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium hornum</i>	(708)	
					<i>Mnium marginatum</i>	(708)	
					<i>Mnium stellare</i>	(708)	
					<i>Plagiomnium undulatum</i>	(708)	
					<i>Plagiothecium undulatum</i>	(708)	
					<i>Taxiphyllum wisgrillii</i>	(708)	
235	β -Barbatene	C ₁₅ H ₂₄			<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium marginatum</i>	(708)	
260	Isobazzanene	C ₁₅ H ₂₄			<i>Mnium marginatum</i>	(708)	
261	β -Bazzanene	C ₁₅ H ₂₄			<i>Mnium hornum</i>	(708)	
					<i>Mnium stellare</i>	(708)	
					<i>Taxiphyllum wisgrillii</i>	(708)	
273	<i>trans</i> - α -Bergamotene	C ₁₅ H ₂₄			<i>Homalia trichomanoides</i>	(708)	
					<i>Plagiothecium undulatum</i>	(708)	

(continued)

Table 5.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
293	Bicyclogermacrene	C ₁₅ H ₂₄			<i>Homalia trichomanoides</i> <i>Mnium marginatum</i> <i>Mnium stellare</i> <i>Taxiphyllum wisgrillii</i> <i>Mnium hornum</i> <i>Mnium marginatum</i> <i>Plagithecium undulatum</i> <i>Mnium marginatum</i> <i>Mnium stellare</i>	(708) (708) (708) (708) (708) (708) (708) (708) (708)	
314	(E)- α -Bisabolene	C ₁₅ H ₂₄			<i>Plagiommium cuspidatum</i> <i>Plagiommium undulatum</i> <i>Taxiphyllum wisgrillii</i>	(784) (708) (708)	
315	β -Bisabolene	C ₁₅ H ₂₄			<i>Plagiothecium undulatum</i> <i>Mnium hornum</i>	(708) (708)	
316	(Z)- γ -Bisabolene	C ₁₅ H ₂₄					
333	<i>ar</i> -Curcumene	C ₁₅ H ₂₂			<i>Plagiothecium undulatum</i> <i>Mnium hornum</i>	(708) (708)	
334	β -Curcumene	C ₁₅ H ₂₄			<i>Plagithecium undulatum</i> <i>Mnium hornum</i>	(784) (708)	
335	γ -Curcumene	C ₁₅ H ₂₄			<i>Plagithecium undulatum</i> <i>Mnium hornum</i>	(708) (708)	
336	β -Bourbonene	C ₁₅ H ₂₄			<i>Plagithecium undulatum</i> <i>Homalia trichomanoides</i>	(708) (708)	
346	γ -Cadinene	C ₁₅ H ₂₄			<i>Plagiothecium undulatum</i> <i>Mnium hornum</i>	(708) (708)	
338	δ -Cadinene	C ₁₅ H ₂₄			<i>Mnium marginatum</i> <i>Mnium stellare</i>	(708) (708)	
353	T-Cadinol	C ₁₅ H ₂₆ O			<i>Homalia trichomanoides</i> <i>Mnium hornum</i>	(708) (708)	
354	α -Cadinol	C ₁₅ H ₂₆ O			<i>Mnium marginatum</i>	(708)	

358	1- <i>epi</i> -Cubenol	C ₁₅ H ₂₆ O	<i>Plagiomnium undulatum</i> (708)
392	α-Murolene	C ₁₅ H ₂₄	<i>Homalia trichomanoides</i> (708)
393	γ-Murolene	C ₁₅ H ₂₄	<i>Plagiomnium undulatum</i> (708)
404	(1 <i>R</i> ,4 <i>R</i>)-Calamenene (= <i>cis</i> -Calamenene)	C ₁₅ H ₂₂	<i>Plagiothecium undulatum</i> (708)
405	(1 <i>S</i> ,4 <i>R</i>)-Calamenene (= <i>trans</i> -Calamenene)	C ₁₅ H ₂₂	<i>Homalia trichomanoides</i> (708)
419	α-Calacorene	C ₁₅ H ₂₀	<i>Plagiothecium undulatum</i> (708)
426	β-Caryophyllene	C ₁₅ H ₂₄	<i>Mnium hornum</i> (708)
430	α-Cedrene	C ₁₅ H ₂₄	<i>Plagiothecium undulatum</i> (708)
432	β-Cedrene	C ₁₅ H ₂₄	<i>Taxiphyllum wisgrillii</i> (708)
435	(-)-β-Cedrene	C ₁₅ H ₂₄	<i>Homalia trichomanoides</i> (708)
436	α-Chamigrene	C ₁₅ H ₂₄	<i>Mnium hornum</i> (708)
455	β-Chamigrene	C ₁₅ H ₂₄	<i>Mnium marginatum</i> (708)
	α-Copaene	C ₁₅ H ₂₄	<i>Mnium stellare</i> (884)
		-10.9 Negative	<i>Plagiomnium acutum</i> (708)
			<i>Plagiomnium undulatum</i> (708)
			<i>Mnium marginatum</i> (708)
			<i>Mnium stellare</i> (708)
			<i>Taxiphyllum wisgrillii</i> (708)
			<i>Homalia trichomanoides</i> (708)
			<i>Mnium hornum</i> (708)
			<i>Mnium marginatum</i> (708)
			<i>Mnium stellare</i> (884)

(continued)

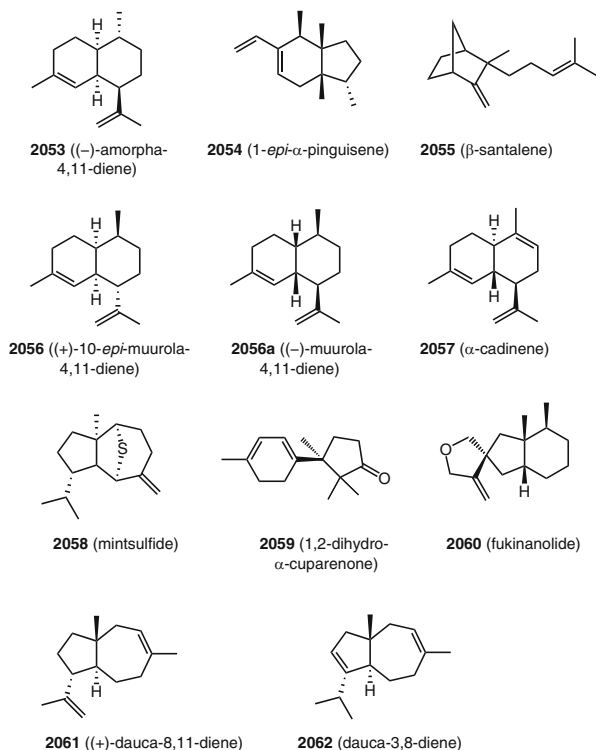
Table 5.3 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
464	Cuparene	C ₁₅ H ₂₂			<i>Mnium marginatum</i>	(708)	
466	α -Cuprenene	C ₁₅ H ₂₄			<i>Mnium stellare</i>	(708)	
467	γ -Cuprenene	C ₁₅ H ₂₄			<i>Mnium stellare</i>	(708)	
468	δ -Cuprenene	C ₁₅ H ₂₄			<i>Mnium hornum</i>	(708)	
483	2-Cuparenol (δ = cuparenol)	C ₁₅ H ₂₂ O			<i>Homalia trichomanoides</i>	(708)	
484	α -Cuprenone	C ₁₅ H ₂₀ O			<i>Plagiomnium cuspidatum</i>	(784)	
550	Peculiaroxide	C ₁₅ H ₂₆ O			<i>Mnium marginatum</i>	(708)	
575	α -Selinene	C ₁₅ H ₂₄			<i>Homalia trichomanoides</i>	(708)	
577	β -Selinene	C ₁₅ H ₂₄			<i>Mnium hornum</i>	(708)	
678	<i>ent</i> -Diplophyllolide [($-$)-eudesma-4,11(13)-dien-12,8-olide]	C ₁₅ H ₂₀ O ₂			<i>Mnium marginatum</i>	(708)	
683	(<i>E</i>)- β -Farnesene	C ₁₅ H ₂₄			<i>Homalia trichomanoides</i>	(708)	
684	(<i>Z,E</i>)- α -Farnesene	C ₁₅ H ₂₄			<i>Taxiphyllum wisgrillii</i>	(708)	
692	Germaecene D	C ₁₅ H ₂₄			<i>Homalia trichomanoides</i>	(708)	
702	1(10),5-Germacradien-4-ol	C ₁₅ H ₂₆ O			<i>Mnium marginatum</i>	(708)	
766	α -Humulene	C ₁₅ H ₂₄			<i>Plagiothecium undulatum</i>	(708)	
777	Longicyclene	C ₁₅ H ₂₄			<i>Mnium marginatum</i>	(708)	
778	Longifolene	C ₁₅ H ₂₄			<i>Mnium stellare</i>	(708)	
					<i>Plagiothecium undulatum</i>	(708)	
					<i>Taxiphyllum wisgrillii</i>	(708)	
					<i>Plagiothecium undulatum</i>	(708)	
					<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium hornum</i>	(708)	

782	α -Longipinene	$C_{15}H_{24}$	<i>Plagiothecium undulatum</i>	(708)
783	β -Longipinene	$C_{15}H_{24}$	<i>Plagiothecium undulatum</i>	(708)
792	Sativene	$C_{15}H_{24}$	<i>Plagiothecium undulatum</i>	(708)
796	γ -Maaliene	$C_{15}H_{24}$	<i>Plagiothecium undulatum</i>	(708)
797	Maali-1,3-diene	$C_{15}H_{22}$	<i>Mnium marginatum</i>	(708)
800	Maalian-5-ol	$C_{15}H_{26}O$	<i>Homalia trichomanoides</i>	(708)
862	Deoxopinguisone	$C_{15}H_{22}O$	<i>Mnium marginatum</i>	(708)
			<i>Mnium hornum</i>	(708)
892	β -Santalene	$C_{15}H_{24}$	<i>Mnium hornum</i>	(708)
922	β -Funebrene	$C_{15}H_{24}$	<i>Taxiphyllum wisgrillii</i>	(708)
932	Sesquisabinene	$C_{15}H_{24}$	<i>Homalia trichomanoides</i>	(708)
2053	(-)-Amorpha-4,11-diene	$C_{15}H_{24}$	<i>Mnium marginatum</i>	(708)
2054	1- <i>epi</i> - α -Pinguisene	$C_{15}H_{24}$	<i>Plagiothecium undulatum</i>	(708)
2055	<i>epi</i> - β -Santalene	$C_{15}H_{24}$	<i>Plagiomnium undulatum</i>	(708)
2056	10- <i>epi</i> -Murola-4,11-diene	$C_{15}H_{24}$	<i>Mnium marginatum</i>	(708)
2057	α -Cadinene	$C_{15}H_{24}$	<i>Homalia trichomanoides</i>	(708)
			<i>Mnium hornum</i>	(708)
			<i>Mnium stellare</i>	(708)
2058	Zonarene	$C_{15}H_{24}$	<i>Taxiphyllum wisgrillii</i>	(708)
2059	Mintsulfide	$C_{15}H_{24}S$	<i>Homalia trichomanoides</i>	(708)
2060	1,2-Dihydro- α -cuparenone	$C_{15}H_{22}O$	<i>Homalia trichomanoides</i>	(708)
2061	Fukinanolide	$C_{15}H_{22}O_2$	<i>Mnium hornum</i>	(708)
2062	Dauca-8,11-diene	$C_{15}H_{24}$	<i>Mnium hornum</i>	(708)
			<i>Plagiothecium undulatum</i>	(708)

as shown in Table 4.2. It is noteworthy that a cadinane sesquiterpene, zonarene (**2058**), which has been isolated from the brown alga, *Dictyopteris zonarioides* (**217**), has been detected in *Homalia trichomanoides*.

ar-Curcumene (**333**) was detected in the ether extract (**784**) and essential oil obtained from *Mnium hornum* (**708**). β -Acoradiene (**69**) was also identified in *Mnium hornum* (**784**), *M. marginatum*, *M. stellare*, and *Taxiphyllum wisgrillii* (**708**). β -Bisabolene (**315**) and 2-cuparenol (δ -cuparenol) (**483**) were elaborated in *Plagiomnium cuspidatum* (**784**). The former hydrocarbon was also detected in *M. marginatum*, *M. stellare*, *P. undulatum*, and *T. wisgrillii* (**708**).



Sesquiterpenoids found in the Bryophyta

The three new sesquiterpene hydrocarbons, (+)-10-epi-muurolo-4,11-diene (**2056**), (-)-1,2-dihydro- α -cuparenone (**2060**), and (+)-dauca-8,11-diene (**2062**), were isolated as major components from the essential oil of *Mnium hornum* and *Plagiomnium undulatum* by preparative GC. The latter species also elaborates (-)-amorpho-4,11-diene (**2053**), the enantiomer of **370**, isolated from the liverwort, *Marsupella aquatica* (**17**, **19**), and (-)- β -cedrene (**432**). *Mnium spinuloum* produces (-)- β -caryophyllene (**426**) as the predominant sesquiterpene hydrocarbon (**708**). The structure of **2060** was elucidated using its 2D-NMR data (COSY, HMQC, HMBC, NOESY). The absolute configuration was deduced by chemical correlations with both (+)-(**393**) and (-)- γ -muurolene (**393**). An excess of the (-)-enantiomer was obtained after partial hydrogenation of the exocyclic double bonds of the γ -muurolene

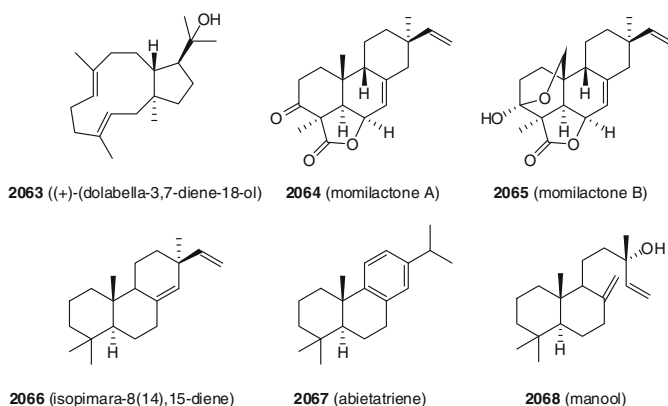
enantiomers and the natural product **2060** (708). The epimer of **2056**, (–)-muurola-4,11-diene (**2056a**), was found in the essential oil of *Amyris balsamifera* (435).

The structure of **2060** was confirmed as (–)-1,2-dihydro- α -cuparenone by ^1H - and ^{13}C NMR spectroscopy and the COSY and HMBC 2D-NMR techniques. Dihydro- α -cuparenone (**486**), the isomer of 1,2-dihydro- α -cuparenone (**2060**), was found in the liverwort *Reboulia hemisphaerica* (550). α -Cuparenone (**484**), which has been isolated from the liverworts *Herbertus aduncus* and *Reboulia hemisphaerica* (40) and *Lepidozia concinna*, *Symphyogyna podophylla*, and *S. prolifera* (72), was also detected in *Mnium marginatum* (708).

The daucane skeleton proposed for **2062** was based on 1D- and 2D-NMR spectroscopic data analysis (COSY, HMBC, HMQC). Its stereochemistry was deduced from a NOESY experiment. In order to determine the absolute configuration of **2062**, a chemical correlation was conducted by comparing the fully hydrogenated products of **2062** with (+)-daucene (**532a**) and dauca-3,8-diene (**2062a**) using enantioselective GC. From **2062a**, four fully hydrogenated products were obtained. From **532a**, four out of eight possible products and two products from compound **2062** were generated. On comparison of all of the hydrogenated products with those prepared from **2062**, the absolute configurations at C-1 and C-5 were determined for this compound (708).

5.1.4 Diterpenoids

Fractionation of the ether extract of the Japanese *Plagiomnium acutum* resulted in the isolation not only of *ent*-cedrenes but also a dolabellane diterpenoid, for which the spectroscopic data and sign of optical rotation, $[\alpha]_{\text{D}} +25.7^\circ \text{cm}^2 \text{g}^{-1} 10^{-1}$, were identical to those of (+)-dolabella-3,7-diene-18-ol (**2063**) (Table 5.4) (884). This compound has been isolated previously from the brown alga, *Dictyota* species (25). This is the first isolation of a dolabellane diterpenoid from the mosses.



Diterpenoids found in the Bryophyta

It is noteworthy that *Plagiomnium acutum* is chemically very similar to some liverworts, which produce both *ent*-sesqui- and *ent*-diterpenoids although the

Table 5.4 Diterpenoids found in the Bryophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1133	16-Kaurene	C ₂₀ H ₃₂			<i>Homalia trichomanoides</i>	(708)	
1154	<i>ent</i> -16 β -Hydroxykaurane	C ₂₀ H ₃₄ O			<i>Physcomitrella patens</i>	(328)	
1316	Phytol	C ₂₀ H ₄₀ O			<i>Mnium hornum</i>	(784)	
					<i>Mnium stellare</i>	(784)	
					<i>Rhizomnium magnifolium</i>	(784)	
					<i>Rhizomnium punctatum</i>	(784)	
					<i>Plagiomnium affine</i>	(784)	
					<i>Plagiomnium elatum</i>	(784)	
					<i>Plagiomnium ellipticum</i>	(784)	
					<i>Plagiomnium medium</i>	(784)	
					<i>Plagiomnium undulatum</i>	(784)	
					<i>Pseudobryum cinclidioides</i>	(784)	
					<i>Plagiomnium cuspidatum</i>	(784)	
1331	Sandaracopimaradiene	C ₂₀ H ₃₂			<i>Plagiomnium acutum</i>	(884)	
2063	(+)-Dolabella-3,7-diene-18-ol	C ₂₀ H ₃₀ O		+25.7	<i>Hypnum plumaeforme</i>	(628)	
2064	Momilactone A	C ₂₀ H ₂₆ O ₃			<i>Hypnum plumaeforme</i>	(628)	
2065	Momilactone B	C ₂₀ H ₂₆ O ₄			<i>Homalia trichomanoides</i>	(708)	
2066	Isopimara-8(14),15-diene	C ₂₀ H ₃₂			<i>Homalia trichomanoides</i>	(708)	
2067	Abietatriene	C ₂₀ H ₃₀			<i>Mnium hornum</i>	(708)	
					<i>Plagiomnium undulatum</i>	(708)	
					<i>Plagiothecium undulatum</i>	(708)	
2068	Manool	C ₂₀ H ₃₄ O			<i>Mnium marginatum</i>	(708)	
					<i>Plagiomnium undulatum</i>	(708)	

plants are morphologically quite different. The *ent*-cedrenes **430** and **432** and the *ent*-dolabellane diterpenoid **2063** are significant chemical markers for *P. acutum*.

Previously, the two pimarane diterpenoids momilactones A (**2064**) and B (**2065**), which were identified as phytoalexins in rice, have been isolated from the moss *Hypnum plumaeforme* (Hypnaceae) (**628**). Momilactone B (**2065**) has been known as an allelopathic agent produced from the roots of rice (**395**) and shown to exhibit cytotoxicity against human colon cancer cells (**409**). *H. plumaeforme* produces relatively high amounts of momilactones (isolated yield 8.4 mg/kg plant for **2064** and 4.2 mg/kg for **2065**), in comparison with those (*ca.* 500 µg/kg) from rice husks. An ethyl acetate extract from *H. plumaeforme* and **2065** showed growth inhibitory activity against angiosperms, mosses, and liverworts, and the crude extract and momilactone B (**2065**) did not affect the growth of this moss (**628**). Thus, the momilactones play an important role as allelochemicals of this species. Momilactones A and B are pimaranes biosynthesized from geranylgeranyl diphosphate in rice (**639**, **941**). However, the mode of biosynthesis of the momilactones in the mosses remains to be clarified (**328**).

Hayashi and associates reported that the moss *Physcomitrella patens*, belonging to the Funariaceae, contains *ent*-16 β -hydroxykaurene (**1154**) and *ent*-kaurene synthase (**328**). The latter is a bifunctional cyclase that synthesizes the *ent*-kaurene skeleton directly from geranylgeranyl diphosphate. This function is distinct from that of higher plants, which synthesize *ent*-kaurane successively using the two cyclases *ent*-copalyl and *ent*-kaurene synthase (**941**).

The ether extracts of 13 mosses were analyzed by GC/MS to demonstrate the presence of sandaracopimaradiene (**1331**) in *Plagiomnium cuspidatum* (**784**). The essential oils obtained from *Homalia trichomanoides*, *Mnium hornum*, *Plagiomnium undulatum*, and *Plagiothecium undulatum* were analyzed by GC/MS to identify abietatriene (**2067**) (**708**), which has been detected in the liverwort *Plagiochila peculiaris* (**40**). 16-Kaurene (**1133**) and manool (**2068**) were also detected in essential oils from *H. trichomanoides*, *Mnium marginatum*, and *Plagiomnium undulatum* (**708**). Both of these compounds have been isolated from many different liverworts, as mentioned earlier, in addition to *Jungermannia torticalyx* (**39**, **40**).

5.2 Steroids and Triterpenoids

The acetone extract of *Polytrichum commune* (Fig. 5.1), belonging to the Polytrichaceae, was fractionated to give 7 α -hydroxysitosterol (**2069**), ergosterol (**2070**), and sitosterol (**1426**) (**233**). The ether extract of the moss *Floribundaria aurea* subsp. *nipponica* (Meteoriaceae) was purified by HPLC to yield a new dammarane triterpene hydrocarbon, dammara-(17*Z*),21-diene (**2071**), together with polypoda-7,13,17,21-tetraene (**2072**) and diploptene (**1435**) (Table 5.5) (**885**). The gross structure of **2071** was derived using the ¹³C NMR data of the known dammara-(17*E*),21-diene (**2071a**) isolated from the fern *Polypodium fauriei* (**36**), except for the signals of C-16, 17, 19, 20, and 28. These observations suggested that **2071** might be a diastereomer at C-18 of **2071a**. The complete structure of **2071** was established by 2D-NMR spectroscopic data analysis (COSY, HSQC, HMBC, and NOESY). The identification of polypoda-7,13,17,21-tetraene (**2072**) from *Floribundaria aurea*



Fig. 5.1 *Polytrichum commune*

subsp. *nipponica* represented the first example of the presence of this compound in a moss, although it has been isolated from the ferns *Polytrichum ovatopaleaceum*, *P. polyblephalum*, and *Cheiropleuria bicuspidis* (384, 743).

The ether extract of *Weymouthia mollis* belonging to the Meteoriaceae was purified by HPLC to afford a hopane triterpene giving spectroscopic data identical to those of 7 β -acetoxyhopan-22-ol (2074) (635), which has been found in some liverworts (40) and lichens (359).

The ether extract of the Chinese moss *Homalia trichomanoides* was chromatographed on silica gel and Sephadex LH-20 to give the three serratane triterpenoids, 3 α -methoxyserrat-14-en-21 β -ol (2075), 3 β -methoxyserrat-14-en-21 β -ol (2076), and 3 β -methoxyserrat-14-en-21-one (2077) (926). All three compounds are known and previously isolated from *Picea jezoensis* (806, 807). A similar compound, 21 α -methoxyserrat-14-en-3-one (1460), has been isolated from the liverwort *Plagiochila asplenoides*, as mentioned earlier (603).

Table 5.5 Steroids and triterpenoids found in the Bryophyta

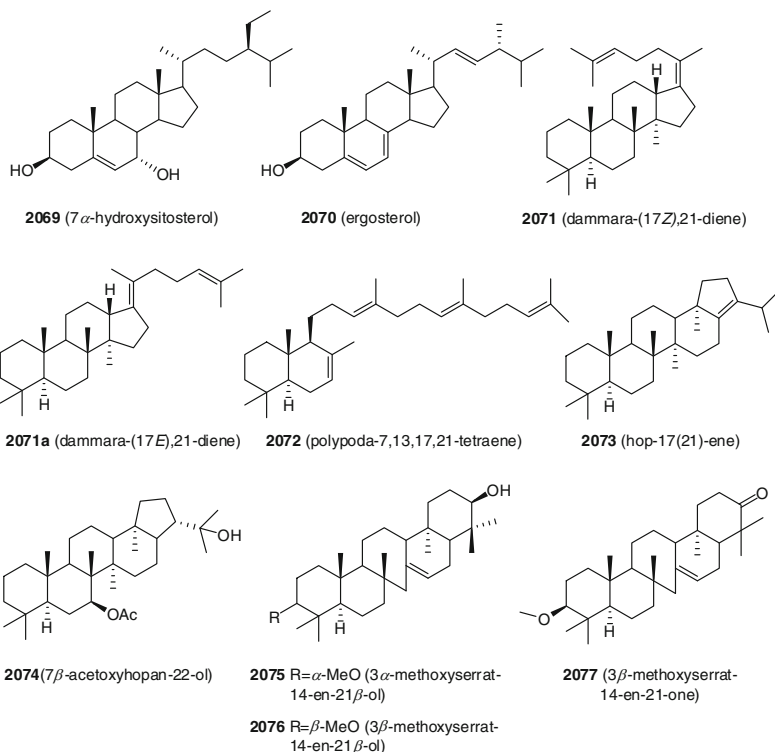
Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /°cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1420	Campesterol	C ₂₈ H ₄₈ O			<i>Mnium hornum</i>	(784)	
					<i>Mnium stellare</i>	(784)	
					<i>Plagiomnium ellipticum</i>	(784)	
					<i>Plagiomnium medium</i>	(784)	
					<i>Plagiomnium undulatum</i>	(784)	
					<i>Plagiomnium vesicatum</i>	(784)	
					<i>Pseudobryum cinctioides</i>	(784)	
					<i>Rhizomnium magnifolium</i>	(784)	
					<i>Rhizomnium punctatum</i>	(784)	
					<i>Trachycystis macrophylla</i>	(784)	
1421	Stigmasterol	C ₂₉ H ₄₈ O			<i>Mnium hornum</i>	(784)	
					<i>Mnium stellare</i>	(784)	
					<i>Plagiomnium ellipticum</i>	(784)	
					<i>Plagiomnium medium</i>	(784)	
					<i>Plagiomnium undulatum</i>	(784)	
					<i>Plagiomnium vesicatum</i>	(784)	
					<i>Pseudobryum cinctioides</i>	(784)	
					<i>Rhizomnium magnifolium</i>	(784)	
					<i>Rhizomnium punctatum</i>	(784)	

(continued)

Table 5.5 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ /cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
1426	Sitosterol	C ₂₉ H ₅₀ O			<i>Trachycystis macrophylla</i>	(784)	
					<i>Mnium hornum</i>	(784)	
					<i>Mnium stellare</i>	(784)	
					<i>Plagiommium elatum</i>	(784)	
					<i>Plagiommium ellipticum</i>	(784)	
					<i>Plagiommium medium</i>	(784)	
					<i>Plagiommium undulataum</i>	(784)	
					<i>Plagiommium vesicatum</i>	(784)	
					<i>Polytrichum commune</i>	(784)	
					<i>Pseudobryum cinclidioides</i>	(784)	
					<i>Rhizomnium magnifolium</i>	(784)	
					<i>Rhizomnium punctatum</i>	(233)	
1432	Squalene	C ₃₀ H ₅₀			<i>Trachycystis macrophylla</i>	(784)	
					<i>Mnium hornum</i>	(784)	
					<i>Plagiommium affine</i>	(784)	
					<i>Plagiommium elatum</i>	(784)	
					<i>Plagiommium ellipticum</i>	(784)	
					<i>Plagiommium medium</i>	(784)	
					<i>Plagiommium undulataum</i>	(784)	
					<i>Rhizomnium magnifolium</i>	(784)	

1435	Diploptene (= Hop-22(29)-ene)	C ₃₀ H ₅₀	<i>Rhizomnium punctatum</i> (784) <i>Floribundaria aurea</i> subsp. nipponica (885) <i>Plagiomnium affine</i> (784) <i>Plagiomnium cuspidatum</i> (784) <i>Plagiomnium ellipticum</i> (784) <i>Plagiomnium medium</i> (784) <i>Plagiomnium undulatum</i> (784) <i>Plagiomnium vesicatum</i> (784) <i>Polytrichum commune</i> (233) <i>Hypnum plumaeforme</i> (233) <i>Floribundaria aurea</i> subsp. nipponica (885) <i>Floribundaria aurea</i> subsp. nipponica (885)
2069	7 α -Hydroxysitosterol	C ₂₉ H ₅₀ O ₂	
2070	Ergosterol	C ₂₈ H ₄₄ O	
2071	Dammara-(17Z),21-diene	C ₃₀ H ₅₀	
2072	Polypoda-7,13,17,21-tetraene	C ₃₀ H ₅₀	50
2073	Hop-17(21)-ene	C ₃₀ H ₅₀	<i>Rhizomnium magnifolium</i> (784) <i>Rhizomnium punctatum</i> (784) <i>Weymouthia mollis</i> (635) <i>Homalia trichomanoides</i> (926) <i>Homalia trichomanoides</i> (926) <i>Homalia trichomanoides</i> (926)
2074	7 β -Acetoxypopan-22-ol	C ₃₂ H ₅₂ O ₃	
2075	3 α -Methoxyserrat-14-en-21 β -ol	C ₃₀ H ₅₂ O ₂	276–277
2076	3 β -Methoxyserrat-14-en-21 β -ol	C ₃₀ H ₅₂ O ₂	305–307
2077	3 β -Methoxyserrat-14-en-21-one	C ₃₀ H ₅₀ O ₂	270–273



Sterols and triterpenoids found in the Bryophyta

5.3 Aromatic Compounds

Previously, several simple aromatic compounds like benzaldehyde, benzyl alcohol, benzoic acid, and cinnamic acid and their derivatives have been identified in many mosses. Flavonoids are ubiquitous constituents in mosses. Altogether, 73 flavonoids including their glycosides have been isolated from or detected in a number of mosses (40). Since 1995, several new types of aromatic compounds have been isolated from mosses as shown in Table 5.6.

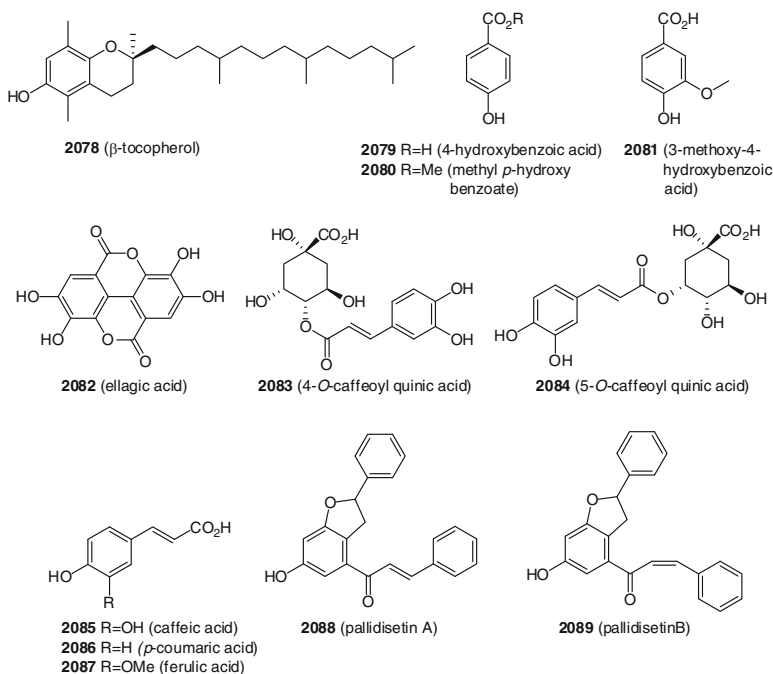
Table 5.6 Aromatic compounds found in the Bryophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25} \text{ cm}^2 \text{ g}^{-1} 10^{-1}$	Plant source(s)	Reference(s)	Comments
1493	3-Methoxybibenzyl	$\text{C}_{15}\text{H}_{16}\text{O}$			<i>Homalia trichomanoides</i> <i>Mnium hornum</i> <i>Mnium marginatum</i> <i>Plagiominium undulatum</i> <i>Plagiothecium undulatum</i> <i>Homalia trichomanoides</i> <i>Mnium stellare</i> <i>Plagiominium affine</i> <i>Plagiominium ellipticum</i> <i>Eucladium verticillatum</i> <i>Homalia trichomanoides</i> <i>Mnium hornum</i> <i>Mnium stellare</i> <i>Plagiominium affine</i> <i>Plagiominium cuspidatum</i> <i>Plagiominium medium</i> <i>Plagiominium undulatum</i> <i>Plagiominium medium</i> <i>Polytrichum commune</i> <i>Eucladium verticillatum</i> <i>Polytrichum commune</i>	(708) (708) (708) (708) (708) (926) (784) (784) (784) (3) (926) (784) (784) (784) (784) (784) (784) (233) (3) (233)	
1738	Atratic acid (= 2,4-Dihydroxy-3,6-dimethylbenzoic acid methyl ester)	$\text{C}_{10}\text{H}_{12}\text{O}_4$	143–145				
1829	Benzyl benzoate	$\text{C}_{14}\text{H}_{12}\text{O}_2$					
1828	Atranorin	$\text{C}_{19}\text{H}_{18}\text{O}_8$	177–179				
1876	α -Tocopherol	$\text{C}_{29}\text{H}_{50}\text{O}_2$					
2078	β -Tocopherol	$\text{C}_{28}\text{H}_{48}\text{O}_2$					
2079	4-Hydroxybenzoic acid	$\text{C}_7\text{H}_6\text{O}_3$					
2080	Methyl 4-hydroxybenzoate	$\text{C}_8\text{H}_8\text{O}_3$					
2081	3-Methoxy-4-hydroxybenzoic acid	$\text{C}_8\text{H}_8\text{O}_4$					
2082	Ellagic acid	$\text{C}_{14}\text{H}_{16}\text{O}_8$			<i>Brachiteciastrum velutinum</i>	(371)	(continued)

Table 5.6 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20} \text{cm}^2 \text{g}^{-1} 10^{-1}$	Plant source(s)	Reference(s)	Comments
2083	4- <i>O</i> -Caffeoylquinic acid	C ₁₆ H ₁₈ O ₉			<i>Brachytheciasrum velutinum</i>	(371)	
2084	5- <i>O</i> -Caffeoylquinic acid	C ₁₆ H ₁₈ O ₉			<i>Brachytheciasrum velutinum</i>	(371)	
2085	Caffeic acid	C ₉ H ₈ O ₄			<i>Brachytheciasrum velutinum</i>	(371)	
2086	<i>p</i> -Coumaric acid	C ₉ H ₈ O ₃			<i>Brachytheciasrum velutinum</i>	(371)	
2087	Ferulic acid	C ₁₀ H ₁₀ O ₄			<i>Brachytheciasrum velutinum</i>	(371)	
2088	Pallidistetin A	C ₂₃ H ₁₈ O ₃	233 (dec.)	+20.0	<i>Polytrichum pallidiscetum</i>	(984)	
2089	Pallidistetin B	C ₂₃ H ₁₈ O ₃	194 (dec.)	-29.6	<i>Polytrichum pallidiscetum</i>	(984)	
2090	7-Methoxy-5,6,8-trihydroxycoumarin-5-β-glucopyranoside	C ₁₆ H ₁₈ O ₁₁			<i>TetrAPHIS pellucida</i>	(382)	
2091	5,7,8-Trihydroxycoumarin-5-β-(6- <i>O</i> -malonyl-glucopyranoside)	C ₁₈ H ₁₈ O ₁₃			<i>TetrAPHIS pellucida</i>	(382)	
2092	7,8-Dihydroxy-5-methoxycoumarin-7-β-sophorose	C ₂₂ H ₂₈ O ₁₅			<i>TetrAPHIS pellucida</i>	(382)	
2093	5,6,7,8-Tetrahydroxycoumarin-5-β-glucopyranoside	C ₁₅ H ₁₆ O ₁₁			<i>TetrAPHIS pellucida</i>	(382)	
2094	5,6,7,8-Tetrahydroxycoumarin-5-β-(6- <i>O</i> -malonyl-glucopyranoside)	C ₂₁ H ₂₆ O ₁₆			<i>TetrAPHIS pellucida</i>	(382)	
2095	5,7,8-Trihydroxycoumarin-5-β-glucopyranoside	C ₁₅ H ₁₆ O ₁₀			<i>TetrAPHIS pellucida</i>	(382)	
2096	5,7,8-Trihydroxycoumarin-5-β-gentiobioside	C ₂₁ H ₂₆ O ₁₅			<i>TetrAPHIS pellucida</i>	(382)	

2097	5,8-Dihydroxy-7-methoxycoumarin 5- β -glucopyranoside	$C_{16}H_{18}O_{10}$		<i>Tetraphis pellucida</i>	(382)
2098	5-Hydroxy-6-methoxycoumarin-7- <i>O</i> - β -glucopyranoside	$C_{16}H_{18}O_{10}$		<i>Polytrichum commune</i>	(233)
2099	Dimethyl phthalide	$C_{10}H_{10}O_4$		<i>Eucladium verticillatum</i>	(3)
2100	Dimethyl terephthalate	$C_{10}H_{10}O_4$		<i>Eucladium verticillatum</i>	(3)
2101	Trichomanin	$C_{50}H_{38}O_{10}$	242–244	<i>Homalia trochomanoides</i>	(926)
2102	1- <i>O</i> -Methylohoensin B	$C_{25}H_{20}O_5$	275–277 (dec.)	<i>Polytrichum pallidisetum</i>	(984)
2103	1- <i>O</i> -Methyldihydrohoensin B	$C_{25}H_{22}O_5$	185–187 (dec.)	<i>Polytrichum pallidisetum</i>	(984)
2104	1,14-Di- <i>O</i> -Methyldihydrohoensin B	$C_{26}H_{24}O_5$	135–137 (dec.)	<i>Polytrichum pallidisetum</i>	(984)
2105	Ohioensin B	$C_{24}H_{18}O_5$	246–247	<i>Polytrichum ohioense</i>	(984)
2106	Ohioensin H	$C_{23}H_{14}O_5$	270–272	<i>Polytrichum commune</i>	(233)
2107	Fontinalin	$C_{13}H_{15}O_3N$		<i>Fontinalis squamosa</i>	(704)
2108	Harmol propionic acid ester	$C_{14}H_{12}O_3N_2$		<i>Fontinalis squamosa</i>	(704)
2109	7-Hydroxyharmone (= Harmol)	$C_{14}H_{12}O_3N_2$		<i>Fontinalis squamosa</i>	(704)
2110	Diphenyl amine	$C_{12}H_{10}ON$		<i>Eucladium verticillatum</i>	(3)
2111	Methyl indoline-6-carboxylate	$C_{10}H_{11}O_2N$		<i>Polytrichum commune</i>	(233)
2112	5-Hydroxy-7-methoxychromone	$C_{10}H_8O_4$		<i>Polytrichum commune</i>	(233)



Aromatic compounds found in the Bryophyta

5.3.1 Chromanols

GC-MS analysis of two *Mnium* and four *Plagiomnium* species confirmed the presence of α -tocopherol (**1876**) (784). The presence of β -tocopherol (**2078**) was detected only in *Plagiomnium medium* (784). α -Tocopherol is distributed in many liverworts but its β -isomer has not yet been found in the liverworts.

5.3.2 Benzoic Acid Derivatives

Atratic acid (**1738**) and atranorin (**1838**), which are lichen components (359), were purified from the ether extract of the Chinese moss *Homalia trichomanoides* (926). Benzyl benzoate (**1829**) and methyl 4-hydroxybenzoate (**2080**) were isolated from the ether extract of the Egyptian moss, *Eucladium verticillatum* (Pottiaceae). This is the first isolation of these simple aromatic compounds from a moss although 14,000 species are known in the world (3). Benzyl benzoate (**1829**) and benzoic acid have been isolated from the liverwort *Isotachis japonica* and the moss *Splachnum ribrum*, respectively (40). Fractionation of the acetone extract of *Polytrichum*

commune gave 4-hydroxybenzoic acid (**2079**) and 3-methoxy-4-hydroxybenzoic acid (**2081**) (**233**). The liverwort *Asterella lindenbergiana* contains 2- and 4-hydroxybenzoic acid (**2079**) (**39**). The latter has also been identified in the liverwort *Haplomitrium gibbsiae* and the moss *Sphagnum cuspidatum*, and in an aqueous alcoholic extract of the immature capsules from the moss *Mnium hornum* (**40**).

Jackovic and coworkers reported the presence of ellagic acid (**2082**) in a methanol extract of *Brachytheciastrum velutinum* (Brachytheciaceae) (**371**). Ellagic acid (**2082**) has also been identified in the liverwort *Lophocolea bidentata* (**40**).

5.3.3 Cinnamic Acid and Bibenzyl Derivatives

The methanol extracts of *Brachytheciastrum velutinum* and *Kindbergia praelonga* (Brachytheciaceae) were analyzed by reversed-phase HPLC, equipped with a diode-array detector (DAD), to identify 4-*O*-caffeoylquinic acid (**2083**), 5-*O*-caffeoylquinic acid (**2084**), and caffeic acid (**2085**). The latter moss also elaborates *p*-coumaric acid (**2086**) and ferulic acid (**2087**) (**371**).

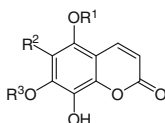
Bioassay-directed fractionation of the ethanol extract of the American moss *Polytrichum pallidisetum* resulted in the isolation of two new cinnamoyl bibenzyls, pallidisetins A (**2088**) and B (**2089**) (**984**). Their structures were assigned as 1-(2,3-dihydro-6-hydroxy-2-phenyl-4-benzofuranyl)-3-phenyl-(*2E*)-propen-1-one (**2088**) and its (*Z*)-isomer (**2089**) by analysis of the NMR spectroscopic data including ¹H-¹H-COSY, 2D-HETCOR and NOE experiments. The pallidisetins might be biosynthesized from the coupling of bibenzyl with cinnamic acid.

The GC/MS analysis of the essential oils of the five mosses, *Homalia trichomanoides*, *Mnium hornum*, *M. marginatum*, *Plagiomnium undulatum*, and *Plagiothecium undulatum*, indicated the presence of 3-methoxybibenzyl (**1493**) (**708**), which has been isolated from three *Radula* liverworts (**40**) and four newly analyzed *Radula* species, as mentioned earlier.

5.3.4 Coumarins

The presence of coumarin derivatives in mosses has been found in *Atrichum undulatum* and *Polytrichum formosum* (**381**). For example, purification of an aqueous methanol extract of *Tetraphis pellucida* (Tetraphidaceae), using medium-pressure liquid chromatography (2% aqueous HCO₂H-MeOH gradient), resulted in the isolation of eight different tri- and tetrahydroxy coumarin derivatives. Among these, three (**2090–2092**) were newly isolated from natural sources and five are the known coumarins 5,6,7,8-tetrahydroxycoumarin-5- β -glucopyranoside (**2093**), 5,6,7,8-tetrahydroxycoumarin-5- β -(6-*O*-malonyl-glucopyranoside) (**2094**),

5,7,8-trihydroxycoumarin-5- β -glucopyranoside (**2095**), 5,7,8-trihydroxycoumarin-5- β -gentiobioside (**2096**), and 5,8-dihydroxy-7-methoxycoumarin-5- β -glucopyranoside (**2097**), which have been found in *Polytrichum formosum* (Polytrichaceae) (382). The structure of **2090** was assigned as 7-methoxy-5,6,8-trihydroxycoumarin-5- β -glucopyranoside from a comparison of the superimposable aromatic signals in its ^{13}C NMR spectrum with those of 7-methoxy-5,6,8-trihydroxycoumarin-5- β -(6-*O*-malonyl-glucopyranoside, isolated from *Polytrichum formosum*, and analysis of FAB-MS, and UV and ^1H NMR spectroscopic data, inclusive of a NOE interaction between the aromatic proton and H-4.



2090 R¹=Glc, R²=OH, R³=Me (7-methoxy-5,6,8-trihydroxycoumarin-5- β -glucopyranoside)

2091 R¹=Malgic, R²=R³=H (5,7,8-trihydroxycoumarin-5- β -(6-*O*-malonyl-glucopyranoside)

2092 R¹=Me, R²=H, R³=Soph (7,8-dihydroxy-5-methoxycoumarin-7- β -sophoroside)

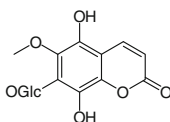
2093 R¹=Glc, R²=OH, R³=H (5,6,7,8-tetrahydroxycoumarin-5- β -glucopyranoside)

2094 R¹=Malgic, R²=OH, R³=H (5,6,7,8-tetrahydroxycoumarin-5- β -(6-*O*-malonyl-glucopyranoside))

2095 R¹=Glc, R²=R³=H (5,7,8-trihydroxycoumarin-5- β -glucopyranoside)

2096 R¹=Gentiob, R²=R³=H (5,7,8-trihydroxycoumarin-5- β -gentiobioside)

2097 R¹=Glc, R²=H, R³=Me (5,8-dihydroxy-7-methoxycoumarin-5- β -glucopyranoside))



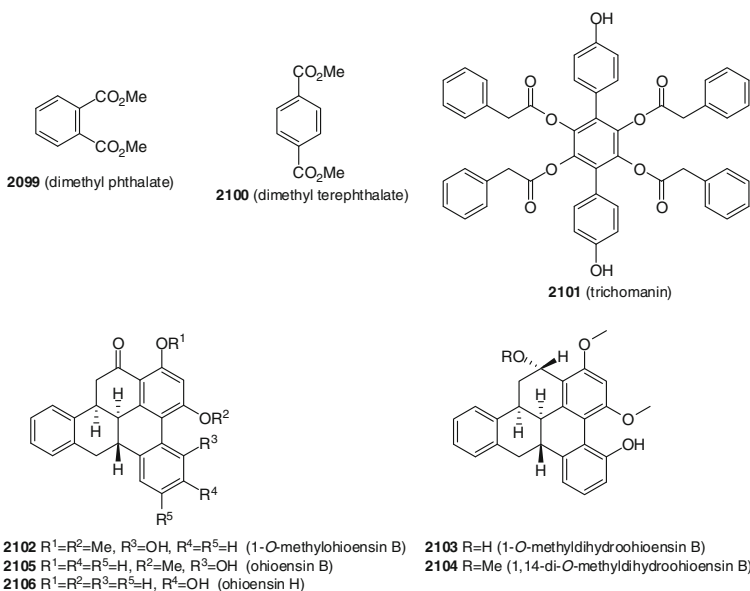
2098 (5-hydroxy-6-methoxycoumarin-7- β -*O*-glucopyranoside)

Coumarin derivatives found in the Bryophyta

Compound **2091** is closely related spectroscopically to the 6'-*O*-malonyl ester of 5,7,8-trihydroxycoumarin-5- β -glucopyranoside (**2095**), which occurs in the Polytrichaceae together with 6-*O*-malonyl- β -glucopyranoside. This was confirmed by FAB-MS and the from the identical aromatic signals in the ^{13}C and ^1H NMR spectra with those of **2095** as well as the signals of the 6-*O*-malonylglucose moiety, which is very close to those of other 6-malonyl- β -glucopyranosides. In addition, a strong AlCl_3 -shift in the UV spectrum was observed. The presence of the monomethyl ether of a trihydroxycoumarin- β -sophoroside in compound **2092** was deduced by means of ^{13}C NMR spectroscopy. The complete structure of **2092** was based on the analysis of its FAB-MS, the ^1H - and ^{13}C NMR spectroscopic data, and from NOE experiments. Thus, the phenolic patterns of the *Tetraphis pellucida* compounds led to their characterization as tri- and tetrahydroxycoumarin derivatives. This pattern is closely related to that found among the coumarin constituents of the Polytrichaceae. The presence of tri- and tetrahydroxycoumarin derivatives is the first characteristic of the gametophytes showing a taxonomic relationship between the Tetraphidaceae and the Polytrichaceae (382). The acetone extract of the Chinese *Polytrichum commune* was purified by column chromatography to give 5-hydroxy-6-methoxycoumarin-7- β -*O*-glucopyranoside (**2098**) (233).

5.3.5 Phthalic Acid Derivatives

Dimethyl phthalate (**2099**) and dimethyl terephthalate (**2100**) were isolated from an ether extract of the Egyptian moss *Eucladium verticillatum* (**3**). This is the first report of the isolation of simple phthalates from the mosses, although dimethyl dimethoxyphthalates have been identified in oxidative and methylated products of five moss species in the genera *Dowsonia*, *Dendroligotrichum*, *Polytrichadelphus*, and *Polytrichum* (**40**). Phthalic acid and its monomethyl ester have been reported from the mushroom *Polyporus dryadeus* var. *brevisporus* (**108**) and the same acid and its dimethyl ester were found in the culture filtrate of the fungus *Gibberella fujikuroi* (**174**).



Phthalates, *p*-terphenyl, and benzonaphthoxanthones found in the Bryophyta

5.3.6 *p*-Terphenyl Derivative

Fractionation of the ether extract of the Chinese moss *Homalia trichomanoides*, belonging to the Neckeraceae, resulted in the isolation of a new *p*-terphenyl derivative named trichomanin (**2101**), for which the structure was established as 4,4''-dihydroxy-1,1':4',1''-terphenyl-2',3',5',6'-tetrayl tetrakis(phenylacetate) on the basis of the interpretation of the 2D-NMR data, X-ray crystallographic analysis, and by alkaline hydrolysis of **2100**, which gave phenyl acetic acid and 1,1':4',1''-terphenyl-

4,2',3',5',6',4''-hexol (926). This is the first isolation of a terphenyl derivative from the mosses although such terphenyls are distributed in many inedible mushrooms (670).

5.3.7 Benzonaphthoxanthenones

As part of the program of the U.S. National Cancer Institute to find antitumor components from bryophytes, two mosses, *Polytrichum* species, *P. ohioense* and *P. pallidisetum*, were investigated chemically and the five ohioensins A-E, which have a new benzonaphthoxanthenone skeleton, were isolated. They showed cytotoxic activity against 9PS and certain other tumor cells in culture (40, 982, 983).

Further fractionation of the 95% ethanol extract of the latter species led to the isolation of the three new benzonaphthoxanthenones, **2102**–**2104**. The structure of **2102** was determined to be 1-*O*-methylohoinsin B or (7b β ,12b α ,14c α)-7b,12b,13,14c-tetrahydro-1,3-dimethoxy-4-hydroxy-1,4*H*-benzo[*c*]naphtho[2,1,8-*mna*]xanthen-14-one, by comparison of the UV and 2D-NMR data (COSY) with those of ohioensin B (**2105**). The structure of **2103** was established not only by comparison of the NMR data with those of **2105** and **2102**, but also by chemical correlation with **2102** and ohioensin B (**2105**). The reduction of **2102** with NaBH₄ gave compound **2103**. The CD spectrum of **2103** was very similar to those of **2102** and **2105**, indicating the compound to be 1-*O*-methylidihydroohioensin B or (7b β ,12b α ,14c α)-7b,12b,13,14c-tetrahydro-1,3-dimethoxy-4,14 α -dihydroxy-1,4*H*-benzo[*c*]naphtho[2,1,8-*mna*]xanthene. The NMR data of compound **2104** showed the same substitution patterns as those of **2103**. The absence of a carbonyl absorption in its IR spectrum suggested that compound **2104** is a benzonaphthoxanthenol, since the molecular formula of **2104** was determined as C₂₆H₂₄O₅. The detailed analysis of its NMR spectroscopic data and the specific optical rotation and CD spectrum of **2104** confirmed the structure of **2104** as 1,14-di-*O*-methylidihydroohioensin B or (7b β ,12b α ,14c α)-7b,12b,13,14c-tetrahydro-1,3,14 α -trimethoxy-4-hydroxy-1,4*H*-benzo[*c*]naphtho[2,1,8-*mna*]xanthene (984).

Purification of the acetone extract of *Polytrichum commune* furnished a new benzonaphthoxanthenone named ohioensin H (**2106**) (233). Comparison of the 1D- and 2D-NMR data (HMBC, NOESY) of ohioensin H (**2106**) with those of the previously known ohioensins, as isolated from *Polytrichum ohioense* and *P. pallidisetum* (984), supported the full structure of **2106** as (7b β ,12b α ,14c α)-1,3,5-trihydroxy-7b,12b,13,14c-tetrahydro-1,4*H*-benzo[*c*]naphtho-[2,1,8-*mna*]xanthen-14-one (233). Ohioensins might be formed from the condensation of *o*-hydroxycinnamate with hydroxylated phenanthrenes or 9,10-dihydrophenanthrenes that originate from the corresponding bibenzyls (983).

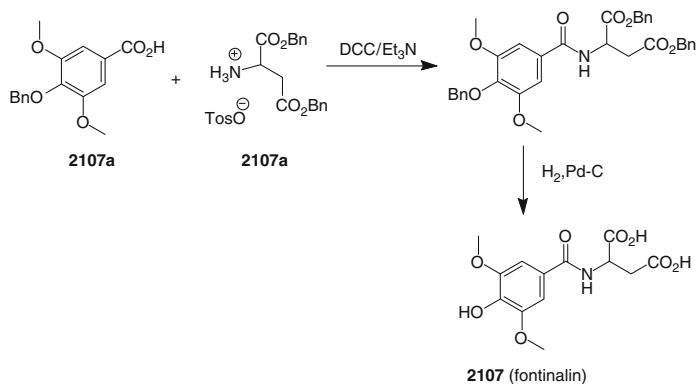
5.3.8 Nitrogen-Containing Compounds

The occurrence of nitrogen-containing metabolites in bryophytes is rare.

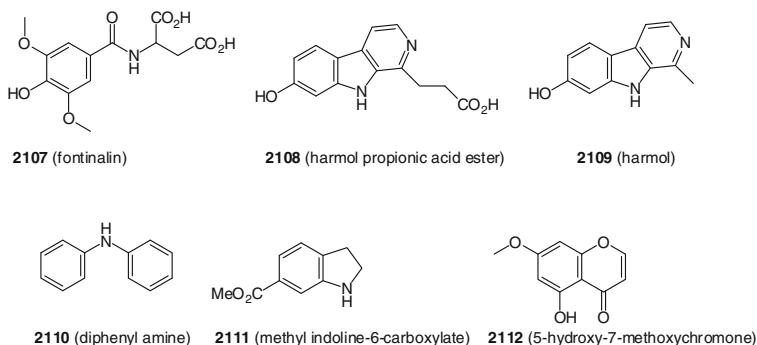
Only a few nitrogen-containing compounds, the prenyl indoles, pyrrolidine, and indole, have been found in the liverworts and the moss *Splachnum rubrum* (40). The

liverwort *Metzgeria rufula* produces rufulamide (**1887**), an oligopeptide analogue combined with malonic and anthranilic acids (**446**). The presence of a cyanogenic glycoside has been shown for the moss *Dicranum scoparium* (**986**).

The methanol-soluble fraction of the dichloromethane extract of the water moss, *Fontinalis squamosa*, belonging to the Fontinalaceae, was purified by medium-pressure liquid chromatography (MPLC) on RP-18 to afford fontinalin (**2107**), harmol propionic acid ester (**2108**), and the harmane alkaloid, 7-hydroxyharmane (= harmol) (**2109**) (**704**), which has been found in different Angiosperm families (**23**). The structure of **2107** was deduced by careful analysis of the ^1H -, ^{13}C -, and ^1H - ^1H COSY NMR data. Conclusive evidence for the structure, *N*-(4-hydroxy-3,5-dimethoxybenzoyl)aspartic acid, was obtained by total synthesis of **2107** by a coupling reaction of *O*-benzyl syringic (**2107a**) acid with the hydrogen tosylate of bibenzyl aspartate (**2107b**) in DCC in the presence of triethyl amine, followed by hydrogenation, which afforded fontinalin (**2107**), as shown in Scheme 5.1 (**704**).



Scheme 5.1 Total synthesis of fontinalin



Nitrogen-containing compounds and a chromone derivative found in the Bryophyta

The NMR spectra of **2108** and the known harmol (**2109**) showed the identity of the aromatic protons and the indole-NH proton, indicating that the structure of **2108**

could be deduced as 3-(7-hydroxy- β -carbolin-1-yl)propionic acid. The structure of this new product was proven by the independent total synthesis of **2108** using a coupling reaction of ethyl 2-(3-phthalimidopropyl)acetoacetate with the diazonium salt of 3-benzyloxyaniline as the key reaction, in eight steps overall (704).

Diphenylamine (**2110**) was isolated from the ether extract of the Egyptian moss, *Eucladium verticillatum* (3). Diphenylamine has been found in green and black tea and onions (386, 627). The acetone extract of *Polytrichum commune* was fractionated to give methyl indoline-6-carboxylate (**2111**) (233).

5.3.9 Chromone Derivative

An acetone extract of *Polytrichum commune* was found to contain 5-hydroxy-7-methoxychromone (**2112**) (233), a compound isolated prior to this from the higher plant, *Artemisia campestris* subsp. *maritima* (915).

5.4 Flavonoids

A review article on the presence of flavonoids in 300 species from 59 different families of mosses has been published (250). Biflavonoids are by far the most common flavonoids in mosses and have been detected in more than two thirds of all moss species. In contrast, the distribution of flavonoid glycosides is rather rare among the mosses, but members of this compound class have been detected in about a quarter of all mosses studied so far. Flavonoid glycosides are very common in the Marchantiophyta (250).

The methanol extracts of *Brachytheciastrum velutinum* and *Kindbergia praelonga* were analyzed by means of reversed-phase HPLC/DAD to identify luteolin (**1888**), apigenin (**1910**), and apigenin-7-*O*-glucoside (**1915**) (Table 5.7) (371).

The methanol-acetone (4:1) extracts of the five mosses *Plagiomnium affine*, *P. cuspidatum*, *Bartramia promiformis* (Bartramiaceae), *Hedwigia ciliata* (Hedwigiaceae), and *Dicranum scoparium* (Dicranaceae) were chromatographed on polyamide-6 and purified on Sephadex LH-20 to give the seven pure flavones, apigenin (**1910**) and vitexin (**2113**) from *P. affine*, saponarin (**2114**) from *P. cuspidatum*, bartramiaflavone (**2115**) from *B. promiformis*, lucenin-2 (**1903**) from *H. ciliata*, and apigenin-7-*O*-triglycoside and luteolin-7-*O*-neohesperidoside (**1900**) from *D. scoparium*. Vitexin (**2113**) was identified for the first time in the moss species *Plagiomnium affine* (106). Luteolin (**1888**), luteolin-7-*O*-neohesperidoside (**1900**), lucenin-2 (**1903**), apigenin (**1910**), and apigenin-7-*O*-glucoside (**1915**) have been identified in several liverworts mentioned earlier and in other mosses (40).

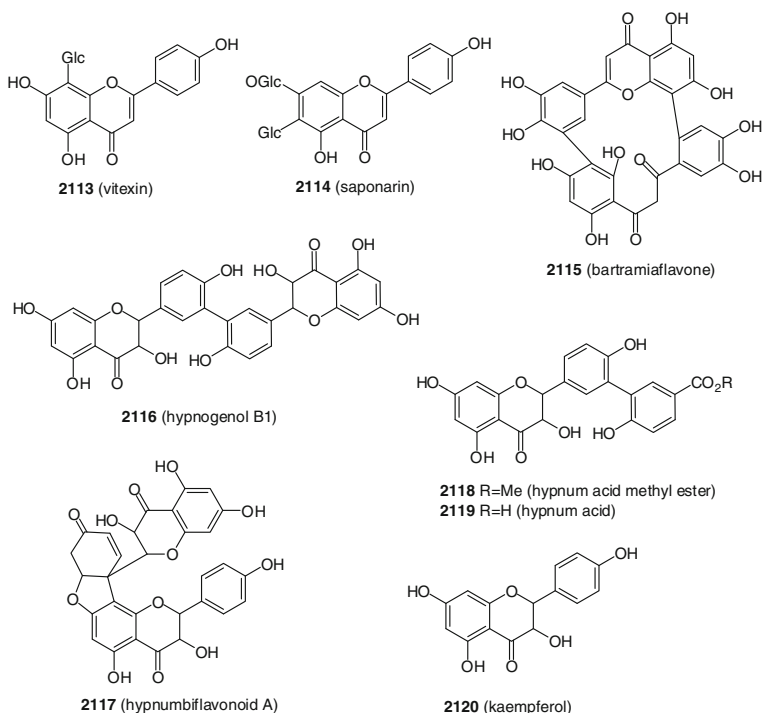
Table 5.7 Flavonoids found in the Bryophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}/\text{cm}^2\text{g}^{-1}\cdot 10^{-1}$	Plant source(s)	Reference(s)	Comments
1888	Luteolin	$\text{C}_{15}\text{H}_{10}\text{O}_6$			<i>Brachytheciastrum velutinum</i>	(371)	
1900	Luteolin-7-O-neohesperidoside	$\text{C}_{27}\text{H}_{30}\text{O}_{15}$			<i>Kindbergia praelonga</i>	(371)	
1903	Lucenin-2	$\text{C}_{27}\text{H}_{30}\text{O}_{16}$			<i>Dicranum scoparium</i>	(106)	
1909	Dicranolomin (= 2,6'-Bisluteolin)	$\text{C}_{30}\text{H}_{18}\text{O}_{12}$			<i>Hedwigia ciliata</i>	(106)	
					<i>Barramia stricta</i>	(249)	
1910	Apigenin	$\text{C}_{15}\text{H}_{10}\text{O}_5$			<i>Aulacomnium palustre</i>	(282)	
					<i>Brachytheciastrum velutinum</i>	(371)	
1915	Apigenin-7-O-glucoside	$\text{C}_{21}\text{H}_{20}\text{O}_{10}$			<i>Kindbergia praelonga</i>	(371)	
					<i>Plagiomnium affine</i>	(106)	
2113	Vitexin	$\text{C}_{21}\text{H}_{20}\text{O}_{10}$			<i>Brachytheciastrum velutinum</i>	(371)	
2114	Saponarin	$\text{C}_{27}\text{H}_{30}\text{O}_{15}$			<i>Kindbergia praelonga</i>	(371)	
2115	Bartramiaflavone	$\text{C}_{30}\text{H}_{18}\text{O}_{13}$			<i>Plagiomnium affine</i>	(106)	
2116	Hypnogenol B1	$\text{C}_{30}\text{H}_{20}\text{O}_{12}$			<i>Plagiomnium cuspidatum</i>	(106)	
2117	Hypnombiflavonoid A	$\text{C}_{30}\text{H}_{20}\text{O}_{12}$			<i>Plagiomnium cuspidatum</i>	(106)	
2118	Hypnum acid methyl ether	$\text{C}_{23}\text{H}_{18}\text{O}_9$			<i>Hypnum cupressiforme</i>	(756)	
2119	Hypnum acid	$\text{C}_{22}\text{H}_{16}\text{O}_9$			<i>Hypnum cupressiforme</i>	(756)	
2120	Kaempferol	$\text{C}_{15}\text{H}_{10}\text{O}_6$			<i>Hypnum cupressiforme</i>	(756)	
2121	Cyclobarramiatriluteolin	$\text{C}_{45}\text{H}_{24}\text{O}_{18}$			<i>Hypnum cupressiforme</i>	(756)	
2122	Philonotisflavone	$\text{C}_{30}\text{H}_{18}\text{O}_{12}$			<i>Barramia stricta</i>	(249)	
					<i>Aulacomnium androgynum</i>	(282)	
2123	Bartramiatriluteolin	$\text{C}_{45}\text{H}_{24}\text{O}_{18}$			<i>Barramia stricta</i>	(249)	
					<i>Barramia stricta</i>	(249)	
					<i>Barramia stricta</i>	(728)	
					<i>Barramia pomiformis</i>	(728)	

(continued)

Table 5.7 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
2124	<i>epi</i> -Bartramiatriluteolin	C ₄₅ H ₂₆ O ₁₆			<i>Bartramia stricta</i>	(728)	
2125	Strictatriluteolin	C ₄₅ H ₂₆ O ₁₇			<i>Bartramia pomiformis</i>	(728)	
					<i>Bartramia stricta</i>	(728)	
2126	5',3'''-Dihydroxyamentoflavone	C ₃₀ H ₁₈ O ₁₂			<i>Bartramia pomiformis</i>	(728)	
2127	5',3'''-Dihydroxyrobustaflavone	C ₃₀ H ₁₈ O ₁₂			<i>Bartramia stricta</i>	(249)	
2128	Aulacomniumblaureusidin	C ₃₀ H ₁₈ O ₁₂			<i>Bartramia stricta</i>	(249)	
2129	Aulacomniumtriluteolin	C ₄₅ H ₂₆ O ₁₈			<i>Aulacomnium paustre</i>	(282)	
					<i>Aulacomnium paustre</i>	(282)	
2130	2,3-Dihydro-5',3'''- dihydroxyamentoflavone	C ₃₀ H ₂₂ O ₁₂			<i>Aulacomnium androgynum</i>	(282)	
2131	2,3-Dihydrophilonotisflavone	C ₃₀ H ₂₀ O ₁₂			<i>Aulacomnium androgynum</i>	(282)	
2132	2,3-Dihydrodicranolomin	C ₃₀ H ₂₂ O ₁₂			<i>Aulacomnium androgynum</i>	(282)	
2133	Communin A	C ₂₃ H ₁₉ O ₃	212–213	–52	<i>Polytrichum commune</i>	(233)	
2134	Communin B	C ₄₅ H ₂₆ O ₁₇	247–250	–47	<i>Polytrichum commune</i>	(233)	
2135	2,3-Dihydro-5'- hydroxyrobustaflavone	C ₃₀ H ₂₂ O ₁₁			<i>Plagiomnium undulatum</i>	(671)	
2136	2,3-Dihydro-5'- hydroxyamentoflavone	C ₃₀ H ₂₀ O ₁₁			<i>Plagiomnium undulatum</i>	(671)	
2137	3'''-Desoxydicranolomin	C ₃₀ H ₁₈ O ₁₁			<i>Plagiomnium undulatum</i>	(671)	
2138	2,3-Dihydro-3'''- desoxydicranolomin	C ₃₀ H ₂₀ O ₁₁			<i>Plagiomnium undulatum</i>	(671)	
2139	2,3-Dihydro-5',3'''- dihydroxyrobustaflavone	C ₃₀ H ₂₀ O ₁₂			<i>Plagiomnium undulatum</i>	(671)	

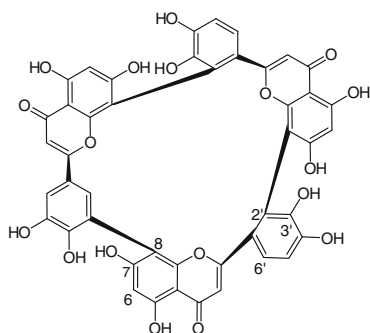


Flavonoids and biflavonoids found in the Bryophyta

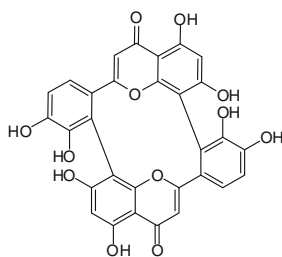
Previously, five new biflavonoids and a 3'-phenylaromadendrin have been found in the moss *Hypnum cupressiforme* (Hypnaceae) (755). All of these flavonoids possess a basic aromadendrin skeleton with a secondary flavonyl or phenyl moiety attached to C-3'. Further fractionation of the methanol extract of the same moss led to the isolation of biflavones named hypnogenol B1 (2116), hypnumbiflavonoid A (2117), hypnum acid methyl ether (2118), hypnum acid (2119), and kaempferol (2120), with the latter representing the first isolation of a flavone aglycone from mosses. All of these compounds were identified by comparison of their NMR spectroscopic data with those of previously known flavonoids (756). Compound 2120 has been identified in the liverwort, *Corsinia coriandrina* (39), and several glycosides of kaempferol (2120) have been found in the liverworts (39) and in mosses including *Bryum* species (40).

Geiger *et al.* (249) reported the isolation of a unique 18-membered macrocyclic triflavonoid named cyclobartramiatriluteolin (2121) from the aqueous acetone extract of *Bartramia stricta* belonging to the Bartramiaceae, together with philonotisflavone (2122), bartramiatriluteolin (2123), dicranolomin (= 2',6''-bisluteolin) (1909), 5',3'''-dihydroxyamentoflavone (2126), and 5',3'''-dihydroxybustafflavone (2127) (248, 727). Compound 1909 has been isolated from the liverwort *Chandonanthus hirtellus*, as mentioned earlier. The ¹³C NMR spectrum of 2121 showed only 15 signals. Their chemical shifts were very closely related to

those of anhydrobartramiaflavone (**2121a**) (248), which is a cyclo-biluteolin derivative possessing a twofold axis of symmetry. The molecular weights of **2121** and **2121a** were determined to be 852 and 568 Da; therefore, **2121** was assigned as a cyclo-triluteolin possessing a threefold axis of symmetry as shown in the structure **2121**. On careful analysis of the ^1H - and ^{13}C NMR spectroscopic data of **2121** and comparison of its spectra with those of **2121a** and luteolin (**1888**) itself, cyclobartramiatriluteolin was characterized as having a tri- head-to-tail-linked luteolin structure (249).

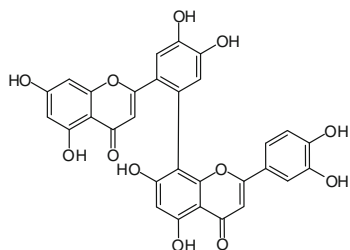


2121 (cyclobartramiatriluteolin)

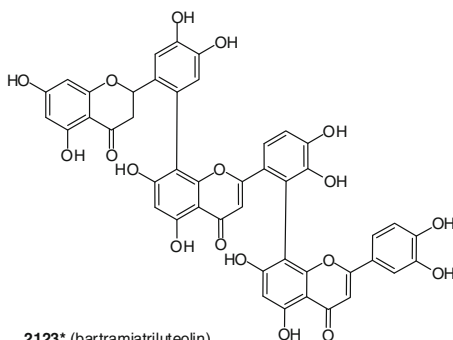


2121a (anhydrobartramiaflavone)

Bi- and triflavonoids found in the Marchantiophyta



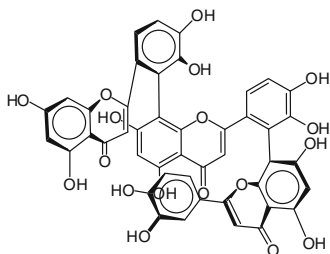
2122 (philonotisflavone)



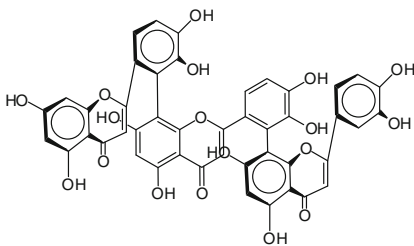
2123* (bartramiatriluteolin)

2124* (*epi*-bartramiatriluteolin)

(*Stereoisomers represented by the same planar formula)

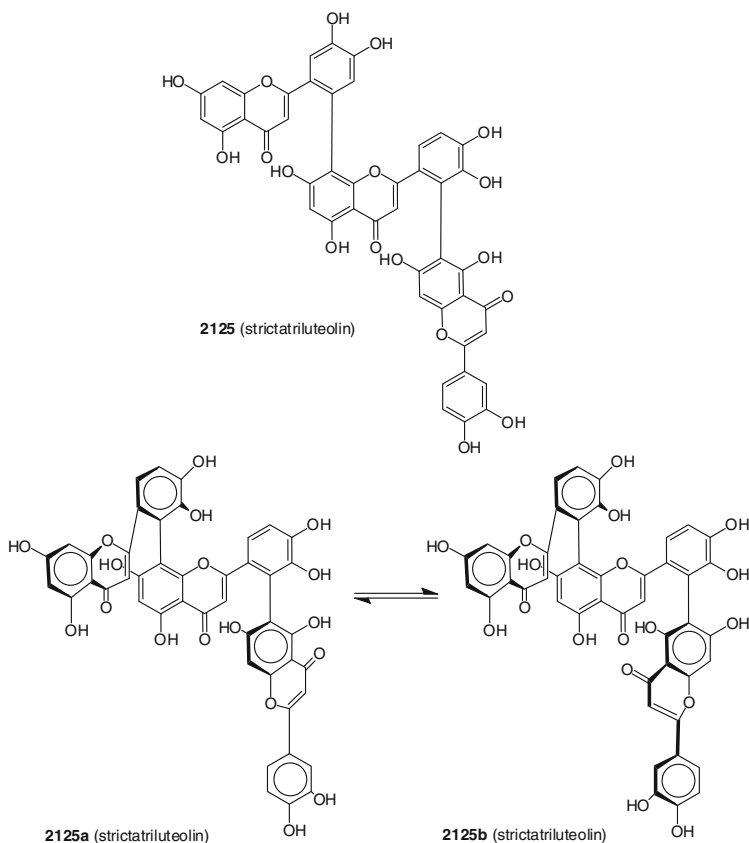


2123 (bartramiatriluteolin)



2124 (*epi*-bartramiatriluteolin)

Bi- and triflavonoids found in the Bryophyta



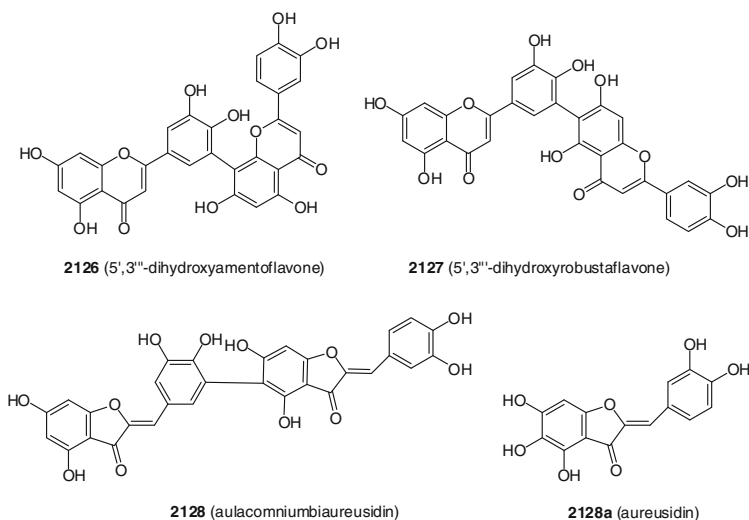
Triflavonoids found in the Bryophyta

A triflavone mixture from *Bartramia stricta* was chromatographed on polyamide and on Sephadex LH-20 at 5°C to afford three triluteolin derivatives, namely, bartramiatriluteolin (**2123**), *epi*-bartramiatriluteolin (**2124**), and strictatriluteolin (**2125**). A small amount of the same mixture was also obtained from *B. pomiformis*. The coupling patterns in the ^1H NMR spectra of **2123** and **2124** were the same, with only the chemical shifts of the proton signals of these two compounds differing significantly. Comparison of the NMR spectroscopic data of compounds **2123**, **2124**, and **2125** with those of various analogues showed that three luteolin units are connected *via* the carbon atoms shown in their structures (727, 728). The structures of the two possible diastereomers **2125a** and **2125b** were confirmed by ROESY NMR data and by comparison of ^1H NMR coupling patterns of **2125** with those of the biluteolins, dicranolomin (**1909**) and philonotisflavone (**2122**) (40). On the basis of ^1H and ^{13}C NMR spectroscopic data, the structure **2125b** represents the major form and compound **2125** contains two interconvertible triluteolin forms, as shown in their structures. These flavone trimers might be the first members of a series of homologous oligoflavonoids constituting the phenolic encrusting substance of the cell walls of a number of mosses (728).

The compounds philonotisflavone (**2122**), bartramiatrilituteolin (**2123**), dicranolomin (= 2',6''-bisluteolin) (**1909**), which has been isolated from the liverwort *Chandonanthus hirtellus*, as mentioned earlier), 5',3'''-dihydroxyamentoflavone (**2126**), and 5',3'''-dihydroxybustaflavone (**2127**) were identified from their NMR spectroscopic data (248, 727) and by co-chromatography with authentic samples from *Bartramia pomiformis* (727) and *Hylocomnium splendens* (110).

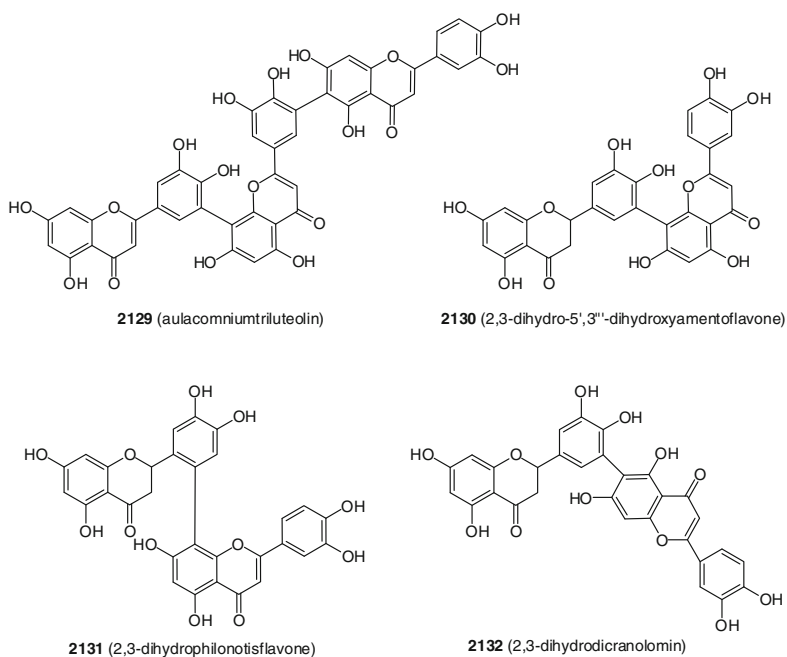
A combination of MPLC and Sephadex LH-20 chromatography performed on an aqueous acetone extract of *Aulacomnium palustre* (Aulacomniaceae) resulted in the isolation of a new biaurone, aulacomniumbiaureusidin (**2128**), and a new triflavone, aulacomniumtriluteolin (**2129**), together with the four known biflavones, 5',3'''-dihydroxyamentoflavone (**2126**), 5',3'-dihydroxyrobustaflavone (**2127**), 2,3-dihydro-5',3'''-dihydroxyamentoflavone (**2130**), and dicranolomin (**1909**), with their structures confirmed by comparison of NMR data with those of published values (31, 248). The comparison of ^{13}C NMR spectroscopic data with those of aureusidin (**2128a**) and also the use of a combination of UV, FAB-MS, and ^1H NMR data, led to the structural assignment of **2128**. This compound exhibited a bright green color, and turned orange after spraying with diphenylboric acid 2-aminoethyl ester (249). The spectroscopic data of **2129** were found to be very similar to those of luteolin (1888) and its dimers, 5',3'''-dihydroxyamentoflavone (**2126**) and 5',3'''-dihydroxyrobustaflavone (**2127**) (31, 248, 520). The triluteolin structure and the sites of the interflavonyl linkages of **2129** were deduced by the careful analysis of its ^1H and ^{13}C NMR data (282).

Aulacomnium androgynum is different chemically from *A. palustre* since the latter species lacks the triflavone, aulacomniumtriluteolin (**2129**). However, it produces the three known biflavonoids philonotisflavone (**2122**), 2,3-dihydrophilonotisflavone (**2131**), and 2,3-dihydrodicranolomin (**2132**) (520). The latter was isolated only once before from *Dicranoloma robustum* (Dicranaceae) (282).



Biflavonoids and the aureusidin dimer **2128** found in the Bryophyta

Polytrichum commune, belonging to the Polytrichaceae, is of interest as medicinal plant for potential cancer chemoprevention (40), as well as to stop bleeding, and as an anti-pneumonia agent, and to treat night sweating and uterine prolapse (233). Purification of the acetone extract of *P. commune* afforded two unusual flavanones named communins A (2133) and B (2134). The stereostructure of **2133** was elucidated as (2*S*,7''*Z*)-7-hydroxy-2-phenyl-5-styrylchroman-4-one from its 2D-NMR spectroscopic data, inclusive of the HMBC and NOESY pulse sequences. The (*S*)-configuration of **2133** at C-2 was supported by a positive *Cotton* effect at 350 nm and a negative one at 305 nm. In turn, the structure and absolute configuration of **2134** were determined to be (2*S*,7''*E*)-7-hydroxy-2-phenyl-5-styrylchroman-4-one, by analysis of 2D-NMR spectroscopic data and the presence of the same sign in the CD curve as seen for **2133**. Communins A (2133) and B (2134) might be biosynthesized by the coupling of different 3,5-dioxohexanoic acids with (*Z*)- or (*E*)-cinnamic acid (233).

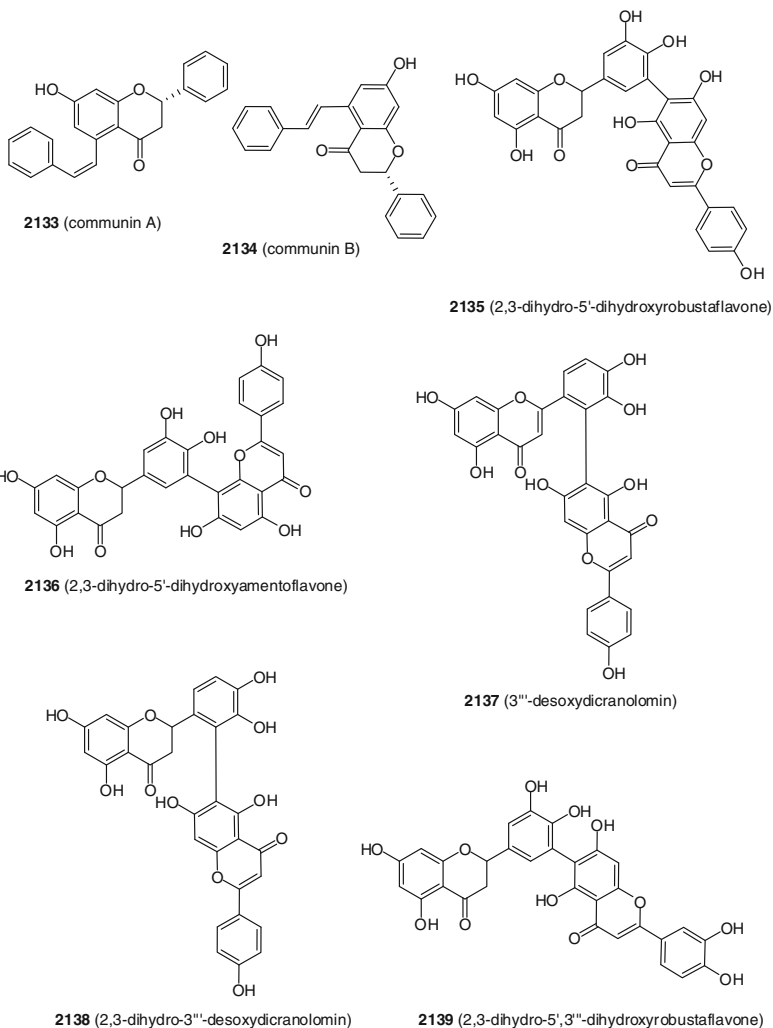


Bi- and triflavonoids found in the Bryophyta

Previously, only flavone *C*- and flavone *O*-glucosides have been isolated from the moss *Plagiomnium undulatum* (638). Further fractionation of an 80% methanol extract of this same moss led to the isolation of the three new bis-flavones **2137–2139**, together with the two known biflavones 2,3-dihydro-5'-hydroxyrobustaflavone (**2135**) and 2,3-dihydro-5'-hydroxyamentoflavone (**2136**) (671).

A combination of the analysis of ^1H and ^{13}C NMR data and their similarity with those of dicranolomin (**1909**) and 2,3-dihydro-5'-hydroxyrobustaflavone (**2135**), along with a consideration of the molecular mass (m/z 554), supported the structure elucidation of the new flavone dimer 3'''-desoxydicranolomin (**2137**). The

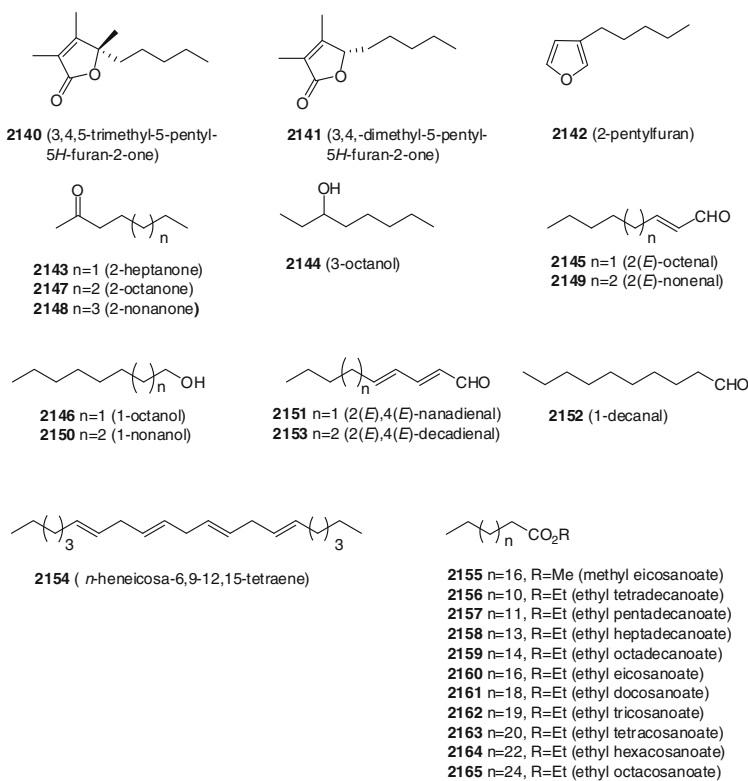
spectroscopic data of **2138** and its molecular mass of 556 Da indicated that **2138** possesses an eriodictyol-apigenin biflavone structure. This was confirmed by comparison of its ^1H NMR spectroscopic data with those of **2137** and 2,3-dihydrodicranolomin (**2132**), which corroborated the structure of 2,3-dihydro-3'''-desoxydicranolomin for **2138**. The comparison of the ^1H NMR data of **2139** with those of **2135** and 5',3'''-dihydroxyrobustaflavone (**2127**) as well as the molecular mass determined (m/z 572), supported the structure of **2139** as 2,3-dihydro-5',3'''-dihydroxyrobustaflavone (**671**). The biflavone profile of *Plagiomnium undulatum* is significantly different from those of *P. elatum* and *P. cuspidatum* (**31**, **40**).



Flavanones and biflavonoids found in the Bryophyta

5.5 Acetogenins and Lipids

From the essential oil of *Plagiomnium undulatum* obtained from the hydrodistillation, the two new butenolides **2140** and **2141** were isolated by preparative GC (Table 5.8). Their structures were established as (+)-3,4,5-trimethyl-5-pentyl-5H-furan-2-one and 3,4-dimethyl-5-pentyl-5H-furan-2-one, by a combination of 1D- and 2D-NMR spectroscopic data analysis (^1H - ^1H -COSY, HMQC, HMBC). *Hylocomium splendens* (Hylocomiaceae) and *H. brevirostre* also produce compound **2141**. The absolute configurations of **2140** and **2141** remain to be clarified. These butenolides are common constituents of mosses (708).



Acetogenins and lipids found in the Bryophyta

The aquatic mosses, *Calliergon cordifolium*, *Drepanocladus lycopodioides* (Amblystegaceae) and *Fontinalis antipyretica* were analyzed for their fatty acid content of total lipids, triacylglycerols, and the diacylglyceryltrimethylhomoserine and phospholipid composition. *C. cordifolium*, *D. lycopodioides*, and *F. antipyretica* produce saturated fatty acids representing 20.5%, 24.2%, and 29.6% of the total lipids, and 23.0%, 30.6%, and 8.3% of the triglycerols. The presence of monoenoic

Table 5.8 Acetogenins and lipids found in the Bryophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25} \text{ cm}^2 \text{ g}^{-1} 10^{-1}$	Plant source(s)	Reference(s)	Comments
1940	1-Octen-3-ol	$\text{C}_8\text{H}_{16}\text{O}$			<i>Plagiomnium undulatum</i>	(708)	
					<i>Taxiphyllum wisgrillii</i>	(708)	
1952	<i>n</i> -Heptanal	$\text{C}_7\text{H}_{14}\text{O}$			<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium hornum</i>	(708)	
					<i>Mnium marginatum</i>	(708)	
					<i>Mnium stellare</i>	(708)	
					<i>Plagiomnium undulatum</i>	(708)	
					<i>Plagiothecium undulatum</i>	(708)	
					<i>Taxiphyllum wisgrillii</i>	(708)	
1953	<i>n</i> -Nonanal	$\text{C}_9\text{H}_{18}\text{O}$			<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium marginatum</i>	(708)	
					<i>Mnium stellare</i>	(708)	
					<i>Plagiomnium undulatum</i>	(708)	
1962	<i>n</i> -Heptadecane	$\text{C}_{17}\text{H}_{36}$			<i>Mnium stellare</i>	(784)	
					<i>Plagiomnium elatum</i>	(784)	
1963	<i>n</i> -Octadecane	$\text{C}_{18}\text{H}_{38}$			<i>Plagiomnium ellipticum</i>	(784)	
					<i>Rhizomnium punctatum</i>	(784)	
					<i>Plagiomnium elatum</i>	(784)	
					<i>Plagiomnium ellipticum</i>	(784)	
1983	Methyl palmitate	$\text{C}_{17}\text{H}_{34}\text{O}_2$			<i>Plagiomnium undulatum</i>	(784)	
					<i>Pseudobryum cinclidioides</i>	(784)	
1984	Ethyl palmitate	$\text{C}_{18}\text{H}_{36}\text{O}_2$			<i>Plagiomnium ellipticum</i>	(784)	
					<i>Pseudobryum cinclidioides</i>	(784)	
1990	Methyl octadecanoate	$\text{C}_{19}\text{H}_{38}\text{O}_2$			<i>Plagiomnium ellipticum</i>	(784)	

1993	Methyl docosanoate	$C_{23}H_{46}O_2$	<i>Plagiominium undulatum</i> (784)
1994	Methyl tetracosanoate	$C_{25}H_{50}O_2$	<i>Plagiominium undulatum</i> (784)
1995	Methyl hexacosanoate	$C_{27}H_{54}O_2$	<i>Pseudobryum cinclidioides</i> (784)
2038	Dihydroanbrettolide	$C_{16}H_{30}O_2$	<i>Pseudobryum cinclidioides</i> (784)
			<i>Mnium stellare</i> (784)
2140	(+)-3,4,5-Trimethyl-5-pentyl-5H-furan-2-one	$C_{11}H_{20}O_2$	<i>Plagiominium elatum</i> (784)
2141	3,4-Dimethyl-5-pentyl-5H-furan-2-one	$C_{11}H_{18}O_2$	<i>Plagiominium medium</i> (784)
			<i>Plagiominium undulatum</i> (708)
2142	2-Pentylfuran	$C_9H_{14}O_3$	<i>Hylocominium splendens</i> (708)
2143	2-Heptanone	$C_7H_{14}O$	<i>Hylocominium brevirostre</i> (708)
2144	3-Octanol	$C_8H_{18}O$	<i>Plagiominium undulatum</i> (708)
2145	2(E)-Octenal	$C_8H_{14}O$	<i>Plagiominium undulatum</i> (708)
			<i>Homalia trichomanoides</i> (708)
2146	1-Octanol	$C_8H_{18}O$	<i>Mnium stellare</i> (708)
2147	2-Octanone	$C_8H_{16}O$	<i>Homalia trichomanoides</i> (708)
			<i>Mnium marginatum</i> (708)
			<i>Mnium stellare</i> (708)
			<i>Plagiominium undulatum</i> (708)
			<i>Plagiothecium undulatum</i> (708)
			<i>Taxiphyllum wisgrillii</i> (708)
2148	2-Nonanone	$C_9H_{18}O$	<i>Plagiothecium undulatum</i> (708)
2149	2(E)-Nonenal	$C_9H_{18}O$	<i>Plagiothecium undulatum</i> (708)

(continued)

Table 5.8 (continued)

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/\text{cm}^2 \text{ g}^{-1} 10^{-1}$	Plant source(s)	Reference(s)	Comments
2150	<i>n</i> -Nonanol	$\text{C}_9\text{H}_{20}\text{O}$			<i>Mnium stellare</i>	(708)	
2151	(2 <i>E</i> ,4 <i>E</i>)-Nonadienal	$\text{C}_9\text{H}_{18}\text{O}$			<i>Taxiphyllum wisgrillii</i>	(708)	
2152	<i>n</i> -Decanal	$\text{C}_{10}\text{H}_{22}\text{O}$			<i>Taxiphyllum wisgrillii</i>	(708)	
2153	(2 <i>E</i> ,4 <i>E</i>)-Decadienal	$\text{C}_{10}\text{H}_{18}\text{O}$			<i>Mnium marginatum</i>	(708)	
					<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium hornum</i>	(708)	
					<i>Plagiomnium undulatum</i>	(708)	
					<i>Plagiothecium undulatum</i>	(708)	
					<i>Taxiphyllum wisgrillii</i>	(708)	
2154	Heneicosa-6,9,12,15-tetraene	$\text{C}_{26}\text{H}_{46}$			<i>Homalia trichomanoides</i>	(708)	
					<i>Mnium marginatum</i>	(708)	
2155	Methyl eicosanoate	$\text{C}_{21}\text{H}_{42}\text{O}_2$			<i>Pseudobryum cinclidioides</i>	(784)	
2156	Ethyl tetradecanoate	$\text{C}_{16}\text{H}_{32}\text{O}_2$			<i>Pseudobryum cinclidioides</i>	(784)	
2157	Ethyl pentadecanoate	$\text{C}_{17}\text{H}_{34}\text{O}_2$			<i>Pseudobryum cinclidioides</i>	(784)	
2158	Ethyl heptadecanoate	$\text{C}_{19}\text{H}_{38}\text{O}_2$			<i>Pseudobryum cinclidioides</i>	(784)	
2159	Ethyl octadecanoate	$\text{C}_{20}\text{H}_{40}\text{O}_2$			<i>Pseudobryum cinclidioides</i>	(784)	
2160	Ethyl eicosanoate	$\text{C}_{22}\text{H}_{44}\text{O}_2$			<i>Pseudobryum cinclidioides</i>	(784)	
2161	Ethyl docosanoate	$\text{C}_{24}\text{H}_{48}\text{O}_2$			<i>Pseudobryum cinclidioides</i>	(784)	
2162	Ethyl tricosanoate	$\text{C}_{25}\text{H}_{50}\text{O}_2$			<i>Pseudobryum cinclidioides</i>	(784)	
2163	Ethyl tetracosanoate	$\text{C}_{26}\text{H}_{52}\text{O}_2$			<i>Pseudobryum cinclidioides</i>	(784)	
2164	Ethyl hexacosanoate	$\text{C}_{28}\text{H}_{56}\text{O}_2$			<i>Pseudobryum cinclidioides</i>	(784)	
2165	Ethyl octacosanoate	$\text{C}_{30}\text{H}_{60}\text{O}_2$			<i>Pseudobryum cinclidioides</i>	(784)	

acids in these three species as total lipids and triglycerols was determined as 18.6–30.1% and 19.1–30.4%. The distribution of mono-acetylenic acids containing a monoene in the three mosses was estimated as 0.3–4.6% (total lipids) and 0.4–15.8% (triglycerols). In terms of the polyenoic acid composition, *C. cordifolium*, *D. lycopodioides*, and *F. antipyretica* showed 60.9%, 47.1%, and 39.9% as total lipids and 57.9%, 41.1%, and 61.3% as triglycerides. The three species elaborate total fatty acids and triglycerols containing low amounts of polyenes. In the case of the triglycerols, *F. fluitans* produced 63.0% of polyene-yne acids. A lesser amount (19.0%) of these acids was detected in *D. lycopodioides*. The 18:3 (n-3) acid proved to be the most abundant fatty acid in both the total lipids and the triglycerols in *C. cordifolium* and *D. lycopodioides*. *Calliergon cordifolium* also produces diacylglycerotrimethylhomoserine (25.6%), phosphatidylcholine (21.4%), phosphatidylglycerol (24.3%), phosphatidylethanolamine (19.6%), phosphatidylseline (3.6%), and phosphatidylinositol (2.9%). *D. lycopodioides* and *F. antipyretica* contain almost the same amounts of these compounds as those found in the liverwort *Riccia fluitans* (190).

The essential oils of the seven mosses *Homalia trichomanoides*, *Mnium hornum*, *M. marginatum*, *M. stellare*, *Plagiomnium undulatum*, *Plagiothecium undulatum*, and *Taxiphyllum wisgrillii* were found to contain various aliphatic aldehydes (*n*-heptanal (1952), *n*-nonanal (1953), (2*E*,4*E*)-decadienal (2153), phenylacetaldehyde), aliphatic alcohols (1-octanol (2146), 1-octen-3-ol (1940)), and aliphatic acids (C₁₂–C₁₈, saturated and mono-di-unsaturated acids and arachidonic acid (2023)), which are abundant in most mosses. Heneicosa-6,9,12,15-tetraene (2154) is also present in most mosses (708).

6 Chemical Constituents of Anthocerotophyta

There are 300 species belonging to the Anthocerotophyta (hornworts), but only a few species have been studied chemically. It is known that the chemical constituents of the Anthocerotophyta are very distinct from the other two classes, the Marchantiophyta and Bryophyta. Previously, several sesquiterpenes and sterols were detected only by GC/MS, while some lignans and cinnamic acid derivatives were isolated from certain hornworts (40). Although the chemical constituents of hornworts have not been investigated fully, *Megaceros flagellaris* is chemically quite different from the other five hornwort genera, *Anthoceros*, *Dendroceros*, *Folioceros*, *Notothylas*, and *Paeroceros* to have been studied so far (40). Furthermore, it is suggested from the presence of simple chemical constituents that the Anthocerotophyta are a more primitive class of plants than the Marchantiophyta (40, 140). Since 1995, several mono-, sesqui-, and phytane-type diterpenoids, rosmarinic glutamic acid derivatives, and chlorophyll degradation products have been isolated from a limited number of hornworts, as shown in Tables 6.1–6.6.

The hornwort *Anthoceros agrestis* produces some glutamic acid amides with 4-hydroxybenzoic, protocatechuic, vanillic, isoferulic, and coumaric acids and the new alkaloid anthocerodiazonin (2173), containing a nine-membered ring system (902).

6.1 Terpenoids

6.1.1 Monoterpenoids

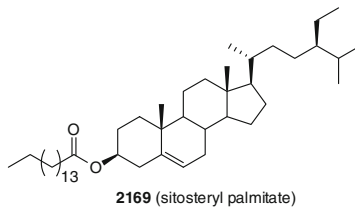
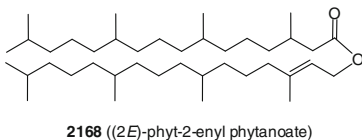
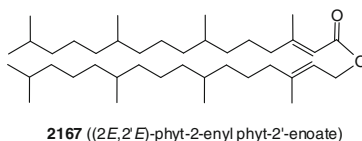
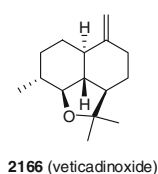
The essential oil prepared by hydrodistillation of a fresh specimen of *Anthoceros caucasicus*, belonging to the Anthocerotaceae and collected in Madeira, was analyzed by GC/MS to identify β -myrcene (1), γ -terpinene (14), terpinolene (15), limonene (19), *p*-cymene (21), α -pinene (47), β -pinene (48), and camphene (55), among which limonene was the major component (540). These monoterpene hydrocarbons are widely distributed in the Marchantiophyta, as mentioned earlier.

Table 6.1 Monoterpenoids found in the Anthocerotophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}/\text{cm}^2 \text{ g}^{-1} 10^{-1}$	Plant source(s)	Reference(s)	Comments
1	β -Myrcene	C ₁₀ H ₁₆			<i>Anthoceros caucasicus</i>	(540)	
14	γ -Terpinene	C ₁₀ H ₁₆			<i>Anthoceros caucasicus</i>	(540)	
15	Terpinolene	C ₁₀ H ₁₆			<i>Anthoceros caucasicus</i>	(540)	
19	Limonene	C ₁₀ H ₁₆			<i>Anthoceros caucasicus</i>	(540)	
21	<i>p</i> -Cymene	C ₁₀ H ₁₄			<i>Anthoceros caucasicus</i>	(540)	
47	α -Pinene	C ₁₀ H ₁₆			<i>Anthoceros caucasicus</i>	(540)	
48	β -Pinene	C ₁₀ H ₁₆			<i>Anthoceros caucasicus</i>	(540)	
55	Camphene	C ₁₀ H ₁₆			<i>Anthoceros caucasicus</i>	(540)	

6.1.2 Norsesquiterpenoids and Sesquiterpenoids

The essential oil *Anthoceros caucasicus* proved to contain a trinorsesquiterpene, 4,8a-dimethyl-4a,5-epoxydecalin (**925**), in addition to a number of sesquiterpene hydrocarbons, namely, aristolene (**108**), calarene (**109**), anastreptene (**122**), viridiflorol (**127**), palustrol (**134**), spathulenol (**136**), *allo*-aromadendrene (**158**), α -barbatene (**234**), β -barbatene (**235**), β -bazzanene (**261**), β -elemene (**283**), β -bisabolene (**315**), β -sesquiphellandrene (**320**), and δ -cuprenene (**468**). Also detected were the sesquiterpene alcohols, rosifoliol (**593**), (*E*)-nerolidol (**687**), maaliol (**798**), and 5-guaiene-11-ol (**736**), the sesquiterpene lactone, diplophyllolide (**678**), and a new sesquiterpene ether named veticadinoxide (**2166**), which was the major volatile oil component (33%), as estimated by GC/MS. The cadinane skeleton of **2166** was based on analysis of the ^1H - ^1H COSY and HMBC NMR spectroscopic data. Its relative configuration was confirmed by means of the NOESY spectrum. Generally, hornworts are considered to be quite poor sources of volatile terpenoids, since members of the Anthocerotophyta do not possess oil bodies. However, *A. caucasicus* proved to elaborate a large amount of the new cadinane-type sesquiterpene ether **2173** ([540](#)).



Sesqui- and diterpenoids and a steroid found in the Anthocerotophyta

Table 6.2 Trinorsesqui- and sesquiterpenoids found in the Anthocerotophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference (s)	Comments
108	Aristolene	C ₁₅ H ₂₄			<i>Anthoceros caucasicus</i>	(540)	
109	Calarene	C ₁₅ H ₂₄			<i>Anthoceros caucasicus</i>	(540)	
122	Anastreptene	C ₁₅ H ₂₂			<i>Anthoceros caucasicus</i>	(540)	
127	Viridiflorol	C ₁₅ H ₂₆ O			<i>Anthoceros caucasicus</i>	(540)	
134	Palustrol	C ₁₅ H ₂₆ O			<i>Anthoceros caucasicus</i>	(540)	
136	Spathulenol	C ₁₅ H ₂₄ O			<i>Anthoceros caucasicus</i>	(540)	
158	<i>allo</i> -Aromadendrene	C ₁₅ H ₂₄			<i>Anthoceros caucasicus</i>	(540)	
234	α -Barbatene	C ₁₅ H ₂₄			<i>Anthoceros caucasicus</i>	(540)	
235	β -Barbatene	C ₁₅ H ₂₄			<i>Anthoceros caucasicus</i>	(540)	
261	β -Bazzanene	C ₁₅ H ₂₄			<i>Anthoceros caucasicus</i>	(540)	
283	β -Elemene	C ₁₅ H ₂₄			<i>Anthoceros caucasicus</i>	(540)	
315	β -Bisabolene	C ₁₅ H ₂₄			<i>Anthoceros caucasicus</i>	(540)	
320	β -Sesquiphellandrene	C ₁₅ H ₂₄			<i>Anthoceros caucasicus</i>	(540)	
468	δ -Cuprenene	C ₁₅ H ₂₄			<i>Anthoceros caucasicus</i>	(540)	
593	Rosifolol	C ₁₅ H ₂₆ O			<i>Anthoceros caucasicus</i>	(540)	
678	Diplophyllolide	C ₁₅ H ₂₀ O ₂			<i>Anthoceros caucasicus</i>	(540)	
687	(<i>E</i>)-Nerolidol	C ₁₅ H ₂₆ O			<i>Anthoceros caucasicus</i>	(540)	
736	5-Guaien-11-ol	C ₁₅ H ₂₆ O			<i>Anthoceros caucasicus</i>	(540)	
798	Maaliol	C ₁₅ H ₂₆ O			<i>Anthoceros caucasicus</i>	(540)	
925	4,8a-Dimethyl-4a,5-epoxydecalin	C ₁₂ H ₂₀ O			<i>Anthoceros caucasicus</i>	(540)	
2166	Veticadimoxide	C ₁₅ H ₂₄ O			<i>Anthoceros caucasicus</i>	(540)	

Table 6.3 Diterpenoids found in the Anthocerotophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25} \text{ cm}^2 \text{ g}^{-1} 10^{-1}$	Plant source(s)	Reference(s)	Comments
1133	<i>ent</i> -16-Kaurene	C ₂₀ H ₃₂			<i>Anthoceros caucasicus</i>	(540)	
1262	Isoabienol	C ₂₀ H ₃₄ O			<i>Anthoceros caucasicus</i>	(540)	
2167	(2 <i>E</i> ,2' <i>E</i>)-Phyt-2-enyl phyt-2'-enoate	C ₄₀ H ₇₆ O ₂		0	<i>Megaceros flagellaris</i>	(140)	
2168	(2 <i>E</i>)-Phyt-2-enyl phytanoate	C ₄₀ H ₇₈ O ₂		0	<i>Megaceros flagellaris</i>	(140)	

Table 6.4 Sterols found in the Anthocerotophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25} \text{ cm}^2 \text{ g}^{-1} 10^{-1}$	Plant source(s)	Reference(s)	Comments
1423	Stigmasteryl palmitate	C ₄₅ H ₇₈ O ₂			<i>Megaceros flagellaris</i>	(140)	
1426	Sitosterol	C ₂₉ H ₅₀ O			<i>Megaceros flagellaris</i>	(140)	
2169	Sitosteryl palmitate	C ₄₅ H ₈₀ O ₂			<i>Megaceros flagellaris</i>	(140)	

6.1.3 Diterpenoids

The diterpenoids, *ent*-16-kaurene (**1133**) and isoabienol (**1262**), have also been detected in the essential oil of *Anthoceros caucasicus*. The ether extract of *Megaceros flagellaris* (Anthocerotaceae) was fractionated to give the two phytol esters (2*E*,2'*E*)-phyt-2-enyl phyt-2'-enoate (**2167**) and (2*E*)-phyt-2-enyl phytanoate (**2168**), which have not been isolated before from a natural source. Analysis of the HMQC, DQF-COSY, and HMBC spectroscopic data confirmed these structures (**140**). The structure of a phytol ester isolated earlier from the liverwort *Monoclea gottschei* subsp. *neotropica* (**771**) was revised to that of the (2'*Z*)-diastereomer, (2*E*,2'*Z*)-phyt-2-enyl-phyt-2'-enoate (**140**).

6.2 Sterols

The hornwort *Megaroceros flagellaris* produces sitosterol (**1426**), stigmasteryl palmitate (**1423**), and sitosteryl palmitate (**2169**), among which sitosterol is the major component (**140**).

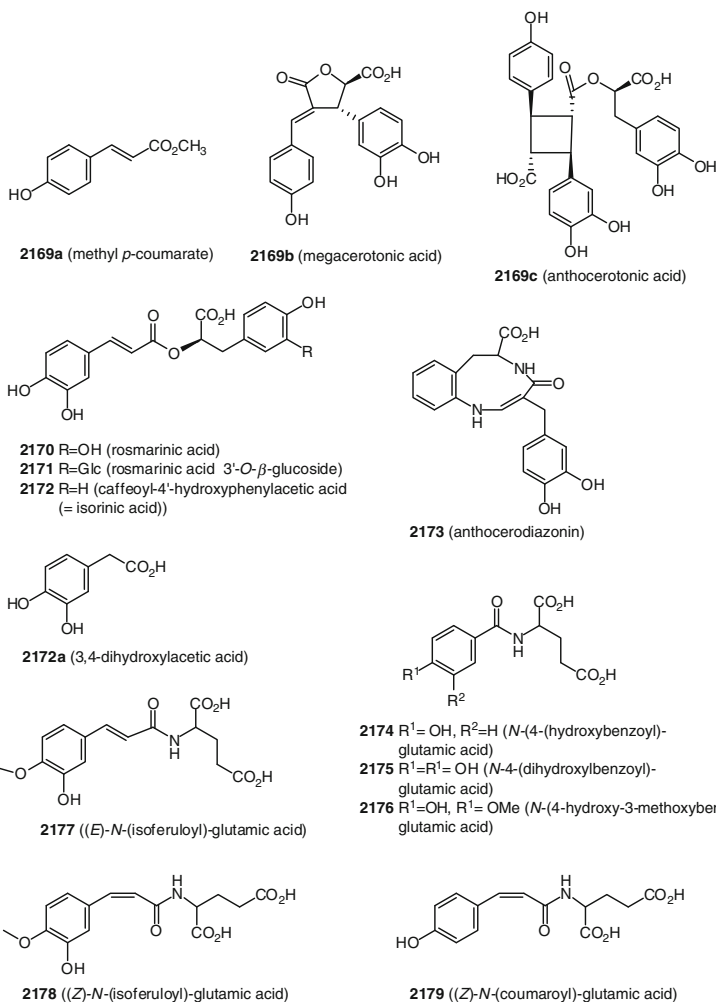
6.3 Aromatic Compounds

6.3.1 Cinnamic Acid Derivatives

Previously, the presence of caffeic acid methyl ester (**1867**) and methyl *p*-coumarate (**2169a**) in *Anthoceros laevis* and caffeic acid (**2085**) in *A. punctatus* has been documented (**40**). It is noteworthy that the Anthocerotophyta species, *A. laevis*, *Dendroceros japonicus* (Dendrocerotaceae), *Megaceros flagellaris*, and *Notothylas temperatae* (Notothyladaceae) produce the lignans, megacerotonic acid (**2169b**), anthocerotonic acid (**2169c**), and (*R*)-rosmarinic acid (**2170**) (**40**). These cinnamic acid derivatives have not yet been isolated from or detected in the Marchantiophyta and the Bryophyta. Investigation of the ethanol extract of a suspension culture of the hornwort *Anthoceros agrestis* resulted in the isolation of the new rosmarinic acid 3'-*O*- β -glucoside (**2171**) and caffeoyl-4'-hydroxyphenylacetic acid (= isorinic acid) (**2172**) (**711**). The latter is a biosynthetic precursor of rosmarinic acid (**2170**), which was also isolated from *A. husnotii* and *A. laevigata* (**917**).

Table 6.5 Aromatic compounds found in the Anthocerotophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{20}$ /cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
2170	Rosmarinic acid	C ₁₈ H ₁₆ O ₈			<i>Anthoceros agrestis</i>	(917)	
2171	Rosmarinic acid 3'-O-β-glucopyranoside	C ₂₄ H ₂₆ O ₁₃			<i>Anthoceros agrestis</i>	(917)	
2172	Cafferoyl-4'-hydroxyphenylacetic acid (= Isorinic acid)	C ₁₈ H ₁₆ O ₇			<i>Anthoceros agrestis</i>	(917)	
2173	Anthocerodiazonin	C ₁₉ H ₁₈ N ₂ O ₅		73	<i>Anthoceros agrestis</i>	(902)	<i>In vitro</i> culture
2174	N-(4-Hydroxybenzoyl)-glutamic acid	C ₁₂ H ₁₃ NO ₆			<i>Anthoceros agrestis</i>	(902)	<i>In vitro</i> culture
2175	N-(3,4-Dihydroxybenzoyl)-glutamic acid	C ₁₂ H ₁₃ NO ₇			<i>Anthoceros agrestis</i>	(902)	<i>In vitro</i> culture
2176	N-(4-Hydroxy-3-methoxybenzoyl)-glutamic acid	C ₁₃ H ₁₅ NO ₇			<i>Anthoceros agrestis</i>	(902)	<i>In vitro</i> culture
2177	(E)-N-(Isoferuloyl)-glutamic acid	C ₁₅ H ₁₇ NO ₇			<i>Anthoceros agrestis</i>	(902)	<i>In vitro</i> culture
2178	(Z)-N-(Isoferuloyl)-glutamic acid	C ₁₅ H ₁₇ NO ₇			<i>Anthoceros agrestis</i>	(902)	<i>In vitro</i> culture
2179	(Z)-N-(p-Coumaroyl)-glutamic acid	C ₁₄ H ₁₅ NO ₆			<i>Anthoceros agrestis</i>	(902)	<i>In vitro</i> culture



Aromatic compounds found in the Anthocerotophyta

The structure of the new glucoside **2171** was determined by a combination of analysis of the 2D-NMR (COSY, HMBC, HMQC, ROESY) and electrospray ionization mass spectrometric data and the enzymatic hydrolysis of **2171**, which gave caffeic acid (**2085**) and 3,4-dihydroxyphenylacetic acid (**2172a**). The presence of the 3'-*O*-glucoside unit was confirmed by the strong NOE correlation between H-1'' and H-2'. The suspension cells of *A. agrestis* accumulated rosmarinic acid (**2170**) and the new glucoside **2171** up to 5.1% and 1.0% of the cell dry weight, respectively ([917](#)).

6.3.2 Alkaloids and Other Nitrogen-Containing Compounds

The ethyl acetate-soluble fraction from the methanol extract of the *in vitro*-cultured *Anthoceros agrestis* was fractionated by column chromatography to give the new alkaloid, anthocerodiazonin (**2173**), together with the six *N*-glutamic acid derivatives, *N*-(3-hydroxybenzoyl)-glutamic acid (**2174**), *N*-(3,4-dihydroxy)-glutamic acid (**2175**), *N*-(4-hydroxy-3-methoxybenzoyl)-glutamic acid (**2176**), (*E*)-*N*-(isoferuloyl)-glutamic acid (**2177**), (*Z*)-*N*-(isoferuloyl)-glutamic acid (**2178**), and (*Z*)-*N*-(*p*-coumaroyl)-glutamic acid (**2179**) (902).

The presence of 1,3,4-tri- and 1,2-disubstituted phenyl rings in **2173** was confirmed by analysis of the chemical shifts and coupling constants in its ¹H NMR spectrum. Furthermore, the presence of a substituted phenylalanine moiety was confirmed by ¹³C NMR spectroscopic data analysis employing COSY and NOE experiments. The nature of the other functional groups and their connectivities were proved by analysis of extensive 2D-NMR data, and the complete structure of **2173** was proposed as (*Z*)-3-(3,4-dihydroxybenzyl)-4-oxo-4,5,6,7-tetrahydro-1*H*-benzo [*f*][1,5]diazonine-6-carboxylic acid. The structures of the other alkaloids were proved by a combination of the molecular formula obtained from CIMS and analysis of the NMR spectroscopic data including NOE experiments. These amides of glutamic acid with benzoic acid are the first such examples among the bryophytes (902).

6.4 Lipids

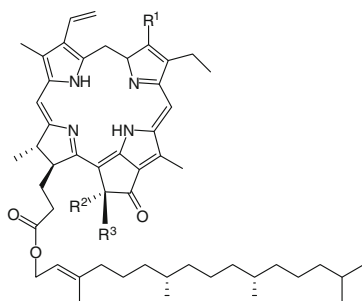
The fatty acid composition of the monogalactosyldiacylglycerols (MGDG) of *Anthoceros agrestis* and the liverwort *Conocephalum conicum* were studied (731). Each fatty acid prepared from MGDG was methylated and the resulting methyl esters analyzed by GC. The most predominant fatty acids of *A. agrestis* were of the 16:3 (n-3) and 18:3 (n-3) types, which comprised together 87% of the total fatty acid content of the MGDG in *A. agrestis*. As mentioned earlier, the major fatty acids of *Conocephalum conicum* were of the 16:3 (n-3) and 18:3 (n-3) types. Thus, the content of fatty acids of *A. agrestis* is very similar to that of *C. conicum*. On the other hand, the proportion of C₂₀-polyenoates was low in *A. agrestis*, like that of the liverworts, suggesting that the older taxon produces less C₂₀ fatty acids than the younger taxon (730).

Table 6.6 Miscellaneous compounds found in the Anthocerotophyta

Formula number	Name of compound	Formula	m.p./°C	$[\alpha]_D^{25}$ cm ² g ⁻¹ 10 ⁻¹	Plant source(s)	Reference(s)	Comments
2046b	Phaeophytin a	C ₅₅ H ₇₄ N ₄ O ₅			<i>Megaceros</i> <i>flagellaris</i>	(140)	
2046f	13 ² -Hydroxy-(13 ² -S)-phaeophytin a	C ₅₅ H ₇₄ N ₄ O ₆			<i>Megaceros</i> <i>flagellaris</i>	(140)	
2046g	13 ² -Hydroxy-(13 ² -R)-phaeophytin a	C ₅₅ H ₇₄ N ₄ O ₆			<i>Megaceros</i> <i>flagellaris</i>	(140)	
2180	Phaeophytin b	C ₅₅ H ₇₄ N ₄ O ₆			<i>Megaceros</i> <i>flagellaris</i>	(140)	
2181	13 ² -Hydroxy-(13 ² -R)-phaeophytin b	C ₅₅ H ₇₂ N ₄ O ₇			<i>Megaceros</i> <i>flagellaris</i>	(140)	
2182	13 ² -Hydroxy-(13 ² -S)-phaeophytin b	C ₅₅ H ₇₂ N ₄ O ₇			<i>Megaceros</i> <i>flagellaris</i>	(140)	
2183	Pyropheophytin a	C ₅₅ H ₇₂ N ₄ O ₃			<i>Megaceros</i> <i>flagellaris</i>	(140)	

6.5 Miscellaneous

Phaeophytin a (**2046e**), 13²-hydroxy-(13²-*S*)-phaeophytin a (**2046f**), 13²-hydroxy-(13²-*R*)-phaeophytin a (**2046g**), phaeophytin b (**2180**), 13²-hydroxy-(13²-*R*)-phaeophytin b (**2181**), 13²-hydroxy-(13²-*S*)-phaeophytin b (**2182**), and pyrophaeophytin a (**2183**), were isolated from an ether extract of the hornwort *Megaceros flagellaris* (**140**). All these phaeophytins are isolated are known natural products. The identification of phaeophytins in this species is reported for the first time in the Anthocerotophyta. The phaeophytins **2046e–2046g**, **2181**, and **2182** have been found in the moss *Entodon rubicundus* (**40**). The liverwort, *Plagiochila ovalifolia* elaborates the same compounds (**2046e–2046h**), as mentioned earlier (**529**). Since it is known that the magnesium atom is very easily lost from chlorophylls, it is very probable that the isolated phaeophytins are artifacts from the isolation procedure used.



2180 R¹=CHO, R²=CO₂Me, R³=H (phaeophytin b)
2181 R¹=CHO, R²=OH, R³=CO₂H (13²-hydroxy-(13²-*R*)-phaeophytin b)
2182 R¹=CHO, R²=CO₂Me, R³=H (13²-hydroxy-(13²-*S*)-phaeophytin b))
2183 R¹=Me, R²=R³=H (pyrophaeophytin a)

Phaeophytins found in the Anthocerotophyta

7 Biologically Active Compounds of the Marchantiophyta and Bryophyta

In earlier reviews (39, 40), chemical constituents isolated from the liverworts (Marchantiophyta) were discussed, possessing characteristic fragrances, bitterness, pungency, and sweetness as well as allergenic contact dermatitis, cytotoxic, antimicrobial, antifungal, calmodulin inhibitory, cardiogenic, insect antifeedant, 5-lipoxygenase inhibitory, molluscicidal, muscle relaxant, neurotrophic, plant growth regulatory, superoxide release inhibitory, thromboxane synthase inhibitory, and vasopressin antagonist activities. Several reviews dealing with biologically active compounds from liverworts have been published more recently (42, 43, 46–50, 80, 85, 290, 568). In this chapter, further biologically active compounds found in liverworts are summarized.

7.1 Fragrance

Almost all liverworts emit intense mushroom-like, sweet woody, or seaweed scents as a result of being crushed. The presence of 1-octen-3-ol (1940) and its acetate (1941) is responsible for the mushroom-like scent of a number of liverworts. Generally, 1-octen-3-yl acetate is more abundant than the free alcohol. A small thalloid liverwort, an *Asterella* species that grows in Pulau Dayang Bunting Island, Malaysia, emits an intense unpleasant odor. It produces two components, namely, skatole (1878), responsible for this smell, representing 20% of the total extract, and 3,4-dimethoxystyrene, (1670), 80% (72). The stink bug smell of the New Zealand *Cheilolejeunea pallidus* is attributable to (*E*)-dec-2-enal (1944), (*Z*)-dec-2-enal (1945), (*E*)-(1942), and (*Z*)-pent-2-enal (1943), although the major components of such insects are (*Z*)- and (*E*)-2-hexenals (860). *Cheilolejeunea imbricata* is a very important species from the view point of fragrance chemistry, because it produces enantiomerically pure (*R*)-dodec-2-en-1,5-olide (1946) and (*R*)-tetradec-2-en-1,5-olide (1947), with a strong milky odor. Although *Leptolejeunea elliptica* is a very tiny liverwort, it emits a powerful, sweet mold-like odor, which is due to the presence of a large amount of the simple alkyl benzenes, 1-ethyl-4-hydroxybenzene

(1796), 1-ethyl-4-methoxybenzene (1797), and 1-ethyl-4-acetoxybenzene (1798) (879).

Gackstroemia decipiens emits a characteristic scent. This odor is due to the presence of a mixture of (–)-13-hydroxybergamota-2,11-diene (275) and the β -santalene derivatives 894–897, which are characterized by their olfactory effects (252). Isoafricanol (89), isolated from the sporophytes of *Pellia epiphylla* as the major component, is responsible for their typical odor (175). *Drepanolejeunea madagascariensis* exhibits a pleasant, sweet, warm, woody-spicy, and herbaceous fragrance. Analysis using the HS-SPME (head space-solid phase microextraction) technique, coupled with GC/MS, has shown that the woody-spicy note is due to a mixture of α -phellandrene (26) and β -phellandrene (27), as well as β -pinene (48), terpinen-4-ol (16), and seven minor sesquiterpene hydrocarbons, β -elemene (283), bicyclogermacrene (293), β -bourbonene (336), δ -cadinene (347), α -copaene (455), α -cubebene (460), and germacrene D (692). The herbaceous odor may be attributable to a combination of *p*-menth-1-en-9-yl acetate (36), *p*-menth-1,8-(9)-dien-10-ol (37), and dill ether (38) (247), with the latter known to be one of the primary odorants of the dill herb *Anethum graveolens* (362, 660). Dill ether (38) is assumed to be key odorant of the fragrance of this liverwort, responsible for the peculiar anise-like odor, with a dill-like impression.

7.2 Pungency

Certain genera of the Marchantiophyta biosynthesize intense pungent compounds, of which some exhibit other interesting biological activities, as described in subsequent sections. The *Porella vernicosa* complex (*P. arboris-vitae*, *P. canariensis*, *P. fauriei*, *P. gracillima*, *P. obtusata* subsp. *macroloba*, *P. roellii*, and *P. vernicosa*) contains very pungent compounds. The strong hot taste of *Porella vernicosa* complex is due to (–)-polygodial (548). Polygodial is the major component of the medicinal plants *Polygonum hydropiper*, *P. minus*, and *P. punctatum* var. *punctatum* (Polygonaceae). It is noteworthy that some ferns, such as *Blechnum fluviatile* collected in New Zealand and the Argentinean *Thelypteris hispida*, elaborate the pungent component, polygodial (548), together with related drimanes (77, 761). An additional pungent substance, 1 β -hydroxysacculatal (1350), was obtained from *Pellia endiviifolia*, together with several sacculatane-type diterpenoids (311). The hot taste of *Pallavicinia levieri* (40) and *Riccardia lobata* var. *yakushimensis* (58) is due to sacculatal (1348), which has been obtained from cell suspension cultures of each liverwort (636, 637).

The New Zealand *Hymenophyton flabellatum* produces a pungent-tasting compound different from those found in the aforementioned liverworts. The hot taste of this species is due to the presence of 1-(2,4,6-trimethoxyphenyl)-but-(2*E*)-en-1-one (1852) (77, 900), which has also been isolated from the Japanese fern, *Arachnoides standishii* (803).

7.3 Allergic Contact Dermatitis

It is well known that several *Frullania* species cause potent allergic contact dermatitis and this phenomenon is ascribed to sesquiterpenes occurring in liverworts with an α -methylene- γ -lactone functionality (39, 40). In Finland, woodcutters sometimes develop allergic contact dermatitis, which is caused by either liverworts (*Frullania*) or lichens growing on the trunks of certain trees. A patient who did not react to sesquiterpene lactones from other possible sources was diagnosed with occupational allergic contact dermatitis from lichens (1).

7.4 Antibacterial, Antifungal, and Antiviral Activities

The essential oil of *Marchesinia mackaii* showed antibacterial activity against *Bacillus subtilis*, *Escherichia coli*, *Salmonella pullorum*, *Staphylococcus aureus*, and *Yersinia enterocolitica* (220).

The herbertane sesquiterpenoids, α -herbertenol (509), β -herbertenol (511), herbertene-1,2-diol (512), mastigophoric methyl ester (516), α -formyl herbertenol (515), 1,2-dihydroxyherberten-12-al (517), and mastigophorene C (530), isolated from the Malagasy *Mastigophora diclados*, were tested against a *Staphylococcus aureus* strain, using an agar diffusion method. These sesquiterpenoids showed weaker activity than the standard antibiotics chloramphenicol and kanamycin. However, of the compounds tested, mastigophorene C (530), a dimer of herbertane-1,2-diol (512), showed the most potent antibacterial activity, while its monomer (512) was less active in this regard (287).

The crude ether and methanol extracts of the Tahitian *M. diclados* showed antimicrobial activity against *Bacillus subtilis* and *Streptococcus aureus* (MIC 16 $\mu\text{g}/\text{cm}^3$) (425). Bioactivity-guided fractionation of both extracts resulted in the isolation of (–)- α -herbertenol (509), (–)-herbertane-1,2-diol (512), mastigophorene A (528), (–)-mastigophorene C (530), (–)-mastigophorene D (531), diplophyllin (676), and (–)-diplophyllolide (678), among which 512, 530, and 531 showed moderate antimicrobial activity against *B. subtilis* at MIC 2–8 $\mu\text{g}/\text{cm}^3$. Only herbertane-1,2-diol (512) indicated weak antimicrobial activity against *Klebsiella pneumoniae* at MIC 100 $\mu\text{g}/\text{cm}^3$ (425).

Sacculatal (1348) from *Pellia endiviifolia* showed potent antibacterial activity against *Streptococcus mutans* (a causative organism for dental caries), exhibiting a LD_{50} value of 8 $\mu\text{g}/\text{cm}^3$. Polygodial (548) was inactive (LD_{50} 100 $\mu\text{g}/\text{cm}^3$) in this same bioassay (85). Lunularin (1477) from *Dumortiera hirsuta* also showed antimicrobial activity against *Pseudomonas aeruginosa* at a concentration of 64 $\mu\text{g}/\text{cm}^3$ (487).

Matsuo and colleagues reported that phaeophytin a (2043), 13²-hydroxy-(13²-S)-phaeophytin a (2044), 13²-hydroxy-(13²-R)-phaeophytin a (2045), and 13²-(MeO₂)-(13²-R)-phaeophytin a (= phaeophytin a hydroperoxide) (2046),

isolated from the methanol-soluble extract of a cell suspension culture of *Plagiochila ovalifolia* showed antimicrobial activity against *Escherichia coli* and *Bacillus subtilis*, but their inhibitory concentrations were not published (529).

Bioautographic TLC assay-guided fractionation of the methylene chloride and methanol extracts of *Bazzania trilobata* resulted in the isolation of six antifungal active sesquiterpenoids, viridiflorol (127), gymnomitrol (240) 5-hydroxycalamenene (406), 7-hydroxycalamenene (408), drimenol (538), and drimenal (540) (715). Viridiflorol (127) has been found to be an antifungal active compound against *Cladosporium cucumerinum* (257). It also showed antifungal activity against *Pyricularia oryzae*. Gymnomitrol (240) showed strong inhibition against *Phytophthora infestans*, *P. oryzae* and *Septoria tritici* (715). 5-Hydroxycalamenene (406) showed inhibitory activity against *Pyricularia oryzae* in a microtiter plate test while 7-hydroxycalamenene (408) had potent antifungal activity against *Botrytis cinerea*, *Cladosporium cucumerinum*, *Phytophthora infestans*, *P. oryzae*, and *Septoria tritici*. Compound 408 was tested for its *in vivo* activity against *Plasmopara viticola* on grape vine leaves and showed inhibitory activity at a concentration of 250 ppm. The infection was reduced from 100% in the control to 30% in the treated plants in a greenhouse (715). Burden and Kemp reported that 7-hydroxycalamenene (408) from *Tilia europaea* is a phytoalexin (144). Drimenol (538) is less active than the calamenenes described above. It inhibited the growth of *C. cucumerinum* and *S. tritici* at concentrations of 6.6 and 80.1 $\mu\text{g}/\text{cm}^3$ (715). Drimenal (540) exhibited moderate growth inhibitory activity against *B. cinerea* and *P. oryzae* and more potent activity against *S. tritici* and *P. infestans* (715).

Dehydrocostus lactone (744), acetyltrifloculoside lactone (745), and 11 α H-dihydrodehydrocostuslactone (746) from *Targionia lorbeeriana* showed antifungal activity against *Cladosporium cucumerinum* with MIC values of 0.5, 10, and 3 $\mu\text{g}/\text{cm}^3$, respectively, using a bioautographic TLC method. Dehydrocostus lactone (744) exhibited the same activity at 20 $\mu\text{g}/\text{cm}^3$ against *C. cucumerinum* in an agar dilution assay. Compound 744 also showed larvicidal activity against *Aedes aegypti*, with a LC_{100} value of 12.5 ppm and antifungal activity against *Candida albicans* (MIC 5 $\mu\text{g}/\text{cm}^3$) in a bioautographic TLC method (620).

Riccardiphenol C (924) from *Riccardia crassa* showed antifungal activity against *Candida albicans* and *Trichophyton mentagrophytes* (651). Glaucescenolide (931), isolated from *Schistochila glaucescens*, exhibited antifungal activity against *Trichophyton mentagrophytes* (712). ent-1 β -Hydroxykauran-12-one (1166), a constituent of *Paraschistochila pinnatifolia*, demonstrated weak antifungal activity against *Candida albicans* (483).

Macrocyclic bis-bibenzyls possess various biological activities, like antimicrobial, antifungal, muscle relaxant, cytotoxicity against KB cells, inhibitory activity against DNA-polymerase β , cardiovascular activity, anti-HIV, and antitumor activity (40, 553).

Niu and coworkers reinvestigated the isolation of the antifungal active bis-(bibenzyls) from *Marchantia polymorpha* using a bioautographic method and found that the bis-bibenzyls plagiochin E, for which the structure was later revised to riccardin D (1567), 13,13'-O-isopropylidene riccardin D (1575), and

neomarchantin A (**1595**) showed antifungal activity against *Candida albicans* with respective *MID* (minimum inhibitory dose) values of 0.2, and 0.4 and 0.25 μg . In turn, riccardin H (**1570**), marchantin A (**1577**), marchantin B (**1578**), and marchantin E (**1581**) showed moderate growth inhibitory activities against the same fungus, with *MID* values of 4.0, 2.5, 4.0, and 2.5 μg , respectively (**624**).

Labbé and associates have suggested that some species of *Riccardia* elaborate high concentrations of the bioactive polychlorinated bibenzyls, 2,6-dichloro-3-hydroxy-4'-methoxybibenzyl (**1553**), 2,6,3'-trichloro-3-hydroxy-4'-methoxybibenzyl (**1554**), 2,4,6,3'-tetrachloro-3-hydroxybibenzyl (**1555**), and 2,4,6,3'-tetrachloro-3,4-dimethoxybibenzyl (**1556**), in order to protect them from pathogens and herbivores (**458**). On TLC-bioautography with a *Cladosporium herbarum* culture, compounds **1553**, **1554**, and **1556** showed fungicidal activities, as manifested by inhibition zones of 1.2–2.9 cm, which were greater than those obtained with the fungicide, ketoconazole. Compound **1555** was inactive against *C. herbarum* (**458**).

Direct TLC bioautographic detection of the antifungal activity of an ether extract of *Asterella angusta* showed activity against *Candida albicans*. Ten bis-bibenzyls, riccardin B (**1565**), riccardin D (**1567**), marchantin H (**1583**), marchantin M (**1587**), marchantin P (**1591**), asterellin A (**1597**), asterellin B (**1598**), 11-demethyl-marchantin I (**1599**), dihydroptychantol (**1600**), and perrottetin E (**1638**), were isolated from this plant and tested against the yeast, *Candida albicans*. All of the compounds tested showed antifungal activity, exhibiting *MIQ* (minimum inhibitory quantity) values between 0.25 and 15.0 μg , and *MIC* (minimum inhibitory concentration) values in the range 16–512 $\mu\text{g}/\text{cm}^3$ (**666**). The free phenolic hydroxy group seems to play an important role in mediating antifungal activity because bis-bibenzyls possessing a methoxy group displayed decreased potencies in this regard (**624**, **715**).

Six bis(bibenzyls), riccardin C (**1566**), riccardin F (**1568**), isoriccardin C (**1571**), marchantin H (**1583**), neomarchantin A (**1595**), and pakyonol (**1601**) isolated from *Plagiochasma intermedium* possessed weak *in vitro* antifungal activity against fluconazole-sensitive and resistant strains of *Candida albicans*, with *MIC*'s ranging from 32 to $>512 \mu\text{g}/\text{cm}^3$. When riccardin C (**1566**) was combined with fluconazole, the synergistic or additive activity of **1566** caused the *MIC*s of fluconazole to be reduced from 256 to $<8 \mu\text{g}/\text{cm}^3$ against three resistant strains of *C. albicans* (**967**).

Guo and associates reported that riccardin D (**1567**) showed antifungal activity against the fluconazole-resistant *Candida albicans* strains, QL-14, QL-28, SDEY-24R, and SDEY-09R with *MIC* values of 16, 32, 16, and 16 $\mu\text{g}/\text{cm}^3$, respectively. When riccardin D (**1567**) was mixed with fluconazole, the antifungal activities were substantially more potent (*MIC* values in the range 0.313–0.375 $\mu\text{g}/\text{cm}^3$) (**274**).

Wu and colleagues demonstrated that the antifungal activity of riccardin D (**1567**) (= plagiochin E) in *Candida albicans* might be attributed to its inhibitory effect on cell wall chitin synthesis (**961**). Riccardin D (**1567**) exerts its antifungal activity through mitochondrial dysfunction-induced reactive oxygen species accumulation in *Candida albicans* (**962**). Riccardin D (**1567**) also induced apoptosis in *Candida albicans* through activating a metacaspase (**963**).

The known bis-bibenzyls, 6',8'-dichloroisoplagiochin C (= bazzanin B) (**1617**), isoplagiochin D (**1607**), and 6'-chloroisoplagiochuin D (= bazzanin S) (**1634**), isolated from *Bazzania trilobata*, showed discernible antifungal activity in a micro-titer plate test against *P. oryzae* and *S. tritici*. Compound **1607** also demonstrated inhibitory activity against *B. cinerea*. Free hydroxy groups on the benzene rings of bis-bibenzyls play an important role in mediating inhibitory activity against fungi such as *C. cucumerinum* (**715**).

Tomentellin (**1748**) and demethoxytomentellin (**1752**) obtained from *Trichocolea tomentella* showed some antifungal activity against *Candida albicans* and *Trichophyton mentagrophytes* (**653**). Methyl-4-[(2*E*)-3,7-dimethyl-2,6-octadienyl]oxy-3-hydroxybenzoate (**1754**), from *T. hatcheri*, showed a lack of antimicrobial activity against *Staphylococcus epidermidis* (MIC 1,000 $\mu\text{g}/\text{cm}^3$) (**93**).

The dichloromethane extract of *Balantiopsis cancellata* demonstrated strong antifungal activity against *Cladosporium herbarum*, a rot fungus, at 0.01 $\mu\text{g}/\text{spot}$. Five aromatic esters, 2-phenylethyl benzoate (**1830**), (*R*)-2-hydroxy-2-phenylethyl benzoate (**1832**), 2-phenylethyl (*Z*)-cinnamate (**1834**), its (*E*)-cinnamate (**1835**), and isotachin B (**1881**) were obtained, among which compound **1881** showed the most potent antifungal activity against *C. herbarum* at 0.006 $\mu\text{g}/\text{spot}$, on TLC-bioautography. This activity is lower than that required with either pure ketoconazole or commercial captan as observed in dilution experiments. The benzoate (**1832**) also showed the same activity as mentioned above at 0.05 $\mu\text{g}/\text{spot}$ (**457**).

Artanorin (**1838**) and 3 β -methoxyserrat-14-en-21 β -ol (**2075**) isolated from the moss *Homalia trichomanoides*, showed antifungal activities against *Candida albicans* with MIC values of 2.0, 2.0, and 0.6 $\mu\text{g}/\text{cm}^3$ (**926**).

Lepidozenolide (**389**) obtained from *Lepidozia fauriana* showed a positive response to methicillin-resistant *Staphylococcus aureus* at 100 $\mu\text{g}/\text{cm}^3$. Compound **389** also showed inhibitory effects on *Candida albicans* and *Trichomonas foetus* at 100 $\mu\text{g}/\text{cm}^3$ (**746**).

The crude extract of *Riccardia marginata* showed antimicrobial activity against the Gram-positive bacterium, *Bacillus subtilis*, and the dermatophytic fungus, *Trichophyton mentagrophytes*. The active compounds are the chlorinated bibenzyls, 2,4,6-trichloro-3-hydroxybibenzyl (**1550**), 2,4-dichloro-3-hydroxybibenzyl (**1551**), and 2-chloro-3-hydroxybibenzyl (**1552**), which showed activity against *B. subtilis*, *T. mentagrophytes*, *Candida albicans*, and the plant pathogenic fungus *Cladosporium resinae*, at a concentration of 30 $\mu\text{g}/\text{per disk}$. However, these compounds proved to be inactive against the Gram-negative bacteria, *Escherichia coli* and *Pseudomonas aeruginosa*. Compound **1551** showed its most potent activities against *T. mentagrophytes* and *C. resinae* (**94**).

Neomarchantins A (**1595**) and B (**1596**) and marchantin C (**1579**) from *Schistochila glaucescens* showed antimicrobial activity against the Gram-positive bacterium, *Bacillus subtilis*, with MIC values of 1.5, 2, and 2 $\mu\text{g}/\text{cm}^3$, and were also active against the dermatophytic fungus *Trichophyton mentagrophytes*, with MIC values, in turn, of 0.5, 1, and 0.5 $\mu\text{g}/\text{cm}^3$ (**712**).

A disk diffusion assay on 2-hydroxy-4,6-dimethoxyacetophenone (**1721**) and 2-hydroxy-3,4,6-trimethoxyacetophenone (**1720**) from *Plagiochila fasciculata* at 150 µg/disk showed both to have antifungal activity against *Trichophyton mentagrophytes* and *Cladosporium resinae*, but not against *Bacillus subtilis* or the Gram-negative bacteria *Escherichia coli* and *Pseudomonas aeruginosa*. At a concentration of 100 µg/cm³, compound **1721** showed inhibitory activities against *E. coli*, *Proteus mirabilis*, and *Staphylococcus aureus*. Compound **1721** also showed antifungal activity against *Candida albicans* (481).

In the critical search for new antituberculosis lead compounds from bryophytes, Scher and his group isolated 14 trachylobane diterpenoids from the liverwort *Jungermannia exsertifolia* subsp. *cordifolia*, among which *ent*-trachyloban-17-al (**1390l**) showed the most potent activity against the virulent *Mycobacterium tuberculosis* H37Rv strain, with a MIC₉₀ value of 24 µg/cm³. *ent*-3β-Acetoxy-19-hydroxytrachylobane (**1390g**), *ent*-trachylobane-3-one (**1390c**), *ent*-3β-hydroxytrachylobane (**1390b**), and *ent*-3β-acetoxytrachylobane (**1390d**) demonstrated moderate inhibitory activities against the same microbe (MIC₉₀ values: 59, 50, 61, and 111 µg/cm³, respectively). The remaining trachylobanes (**1390e**, **1390f**, **1390h**, **1390i**, **1390k**, **1390m**, and **1390o**) showed MICs of >128 µg/cm³ and were thus considered to be inactive (717).

The H1N1 and H5N1 influenza A virus caused pandemics throughout the world in 2009. Influenza A possesses an endonuclease within its RNA polymerase comprised of PA, PB1, and PB2 subunits. In order to obtain potential new anti-influenza compounds, 33 different types of phytochemicals were evaluated using a PA endonuclease inhibition assay *in vitro* (367). Among them, marchantins A (**1577**), B (**1578**), and E (**1581**), plagiocchin A (**1603a**), and perrottetin F (**1639**) inhibited influenza PA endonuclease activity at a concentration of 10 µM. This was the first evidence that the phytochemicals derived from liverworts can inhibit influenza A endonuclease.

7.5 Insect Antifeedant Activity

Lepidolaena claviger produces the clavigerin group of bergamotane sesquiterpenoids. Of these, clavigerin A (**276**) and methoxyclavigerin C (**281**), showed less potent antifeedant activity against larvae of the webbing clothes moth, *Tineola bisselliella* (Lepidoptera) than either clavigerins B (**277**) or C (**278**). The latter compounds were tested also against larvae of the Australian carpet beetle, *Anthrenocerus australis* (Coleoptera), and again showed antifeedant activity. The insect antifeedant activity of the acetoxy acetals **277** and **278** could be due to their proposed facile hydrolysis to the corresponding aldehydes. The activity of plagiocchiline A (**183**), possessing an acetoxy acetal, is also due to the fact that it can hydrolyze to a dialdehyde, which show some biological activity (40, 656, 657). Clavigerins A (**276**) and B (**277**) showed potent antifeedant activity against the larvae of the carpet beetle, with values obtained on wool of 0.026% w/w for **277** and

0.05% w/w for **276**. Both compounds showed significant insecticidal and antifeedant activities against clothes moth larvae at 0.1% w/w. A control substance, azadirachtin, showed activity at 0.007% w/w (**656**).

1-(2,4,6-Trimethoxyphenyl)-but-2(*E*)-en-1-one (**1852**) from *Hymenophyton flabellatum* (**900**) has demonstrated antifeedant activity against larvae of the yellow butterfly, *Eurema hecabe mandarina* (**630**). Isotachin B (β -phenethyl (*E*)- β -methylthioacrylate) (**1881**), from *Balantiopsis cancellata*, showed moderate antifeedant activity against the larvae of *Spodoptera littoralis*, an army worm, at 10 $\mu\text{g}/\text{cm}^2$ (50% deterrence), in a leaf disk assay (**457**). Two chlorinated bibenzyls, 2,6,3'-trichloro-3-hydroxy-4'-methoxybibenzyl (**1554**) and 2,4,6,3'-tetrachloro-3,4'-dihydroxybibenzyl (**1556**), found in *Riccardia polyclada*, were tested against the larvae of *Spodoptera littoralis* and again showed moderate antifeedant activity (**458**).

7.6 Antioxidant Activity

Bioactivity-guided fractionation of the ether and methanol extracts of *Mastigophora dicladus* using the DPPH radical-scavenging assay resulted in the isolation of (–)- α -herbertenol (**509**), (–)-herbertane-1,2-diol (**512**), mastigophorene A (**528**), (–)-mastigophorene C (**530**), (–)-mastigophorene D (**531**), (–)-diplophyllin (**676**), and (–)-diplophyllolide (**678**), among which **512**, **530**, and **531** showed strong antioxidant activity with IC_{50} values of 1.9, 2.7, and 2.0 $\mu\text{g}/\text{cm}^3$. The activities of **512** and **531** were more potent than vitamin C and similar to quercetin (**425**).

Schwartner and colleagues established the formation of *o*-semiquinone radicals from compounds in the marchantin series. Using pulse radiolysis and EPR techniques, in addition to their kinetic data, these compounds were confirmed as effective antioxidants. Perrottetin D (**1541a**) showed the most potent activity of these compounds in an arachidonic acid autoxidation assay (**725**).

Bioactivity-guided fractionation of an ether extract of *Plagiochila ovalifolia* using the DPPH-radical scavenging assay resulted in the isolation of 3,5-dihydroxy-2-(3-methyl-2-butenyl)-bibenzyl (**1525**) and plagiochin D (**1603**), which displayed antioxidative activity (28–48% inhibition at 50–200 $\mu\text{g}/\text{cm}^3$ and 62–78% inhibition at 50–200 $\mu\text{g}/\text{cm}^3$) (**701**).

Marchantin A (**1577**) also showed free-radical scavenging activity at (IC_{50} 20 $\mu\text{g}/\text{cm}^3$) (**355**). Marchantin H (**1583**) showed non-enzymatic iron-induced lipid peroxidation in rat brain homogenates at IC_{50} 0.51 μM (**351**). This effect was more potent than those of desferrioxamine or other classical antioxidants. Compound (**1583**) suppressed NADPH-dependent microsomal lipid peroxidation at IC_{50} 0.32 μM without affecting microsomal electron transport of NADPH-cytochrome P450 reductase. It also inhibited copper-catalyzed oxidation of human low-density lipoprotein. Hsiao and colleagues concluded that marchantin H (**1583**) is a potentially effective and versatile antioxidant, and can be used as a chaperone protecting the biomacrocyclic molecule against peroxidative damage (**351**).

An antioxidative assay on subulatin (**1864**) from *Jungermannia sublata* was carried out using the erythrocyte membrane ghost system. Compound **1723** showed the same activity as that of a positive control, α -tocopherol (**1876**). Tazaki and associates suggested that compound **1864** might play a role in the detoxification of oxygen generated by photo-oxidation in liverworts (**823**). Nishiki and colleagues also predicted that α -tocopherol (**1876**), which has been found in all liverworts, might be a significant antioxidant for the oil bodies of these plants (**623**).

7.7 Antiplatelet Activity

Marchantiaquinone (**1589**), obtained from *Reboulia hemisphaerica*, showed antiplatelet activity at a concentration of $100\text{ }\mu\text{g}/\text{cm}^3$ (**935**). Plagiochiline C (**185**) exhibited significant antiplatelet effects on arachidonate- ($100\text{ }\mu\text{M}$) (95% and 45% inhibition, respectively, at 100 and $50\text{ }\mu\text{g}/\text{cm}^3$) and collagen- ($10\text{ }\mu\text{g}/\text{cm}^3$) (100% inhibition at $100\text{ }\mu\text{g}/\text{cm}^3$ level) induced aggregations of washed rabbit platelets. Isoplagiochilide (**204**) displayed a less potent activity than plagiochiline C (**185**) in this regard (**470**). Lepidozenolide (**389**) and (–)-5 β -hydroperoxylepidozenolide (**390**) from *Lepidozia vitrea* and *L. fauriana* were associated with potent antiplatelet effects on both arachidonate- ($100\text{ }\mu\text{M}$) (100% and 50% inhibition) and collagen- ($10\text{ }\mu\text{g}/\text{cm}^3$) (87 and 93%) induced aggregation of rabbit platelets at the $100\text{ }\mu\text{g}/\text{cm}^3$ level. Compound **389** was the more potent of these two compounds when evaluated against the effects induced by platelet-activating factor ($2\text{ ng}/\text{cm}^3$; 100% inhibition) (**746**).

7.8 Antithrombin Activity

Perrottetin E (**1638**) showed inhibitory activity against thrombin (IC_{50} $18\text{ }\mu\text{M}$), which is associated with blood coagulation (**583**).

7.9 Brine Shrimp Lethality Activity

The dichloromethane extract of *Balantiopsis cancellata* showed potent lethality against the larvae of brine shrimp (*Artemia salina*) at a LD_{50} value of less than 2.5 ppm. All phenyl ethanol esters **1830** and **1832–1835** tested showed inhibitory activities against brine shrimp larvae at concentrations of 2.5–7.4 ppm (**457**). In a further study on other constituents of this same species, the chlorinated bibenzyls **1553–1556** showed brine shrimp (*Artemia salina*) lethality activity at LC_{50} 0.42–2.35 ppm, and were compared with values obtained for the standard substances ketoconazole (LC_{50} 14.9 ppm) and Asuntol® (LC_{50} 10.8 ppm) (**458**).

7.10 Calcium Inhibitory Activity

Conformational analysis of riccardin A (**1564**) and marchantin A (**1577**) was carried out by systematic unbounded multiple minimum search (SUMM). Mobility of the macrocyclic rings of both compounds was analyzed by a variable temperature (20–100°C) ^1H NMR study. The results indicated the restricted mobility of the macrocyclic ring of riccardin A (**1564**) and gave further evidence for its more rigid nature in comparison to marchantin A (**1577**). Comparing the calcium inhibitory activity of **1564** and **1577** (ID_{50} : 20 and $1.85\ \mu\text{g}/\text{cm}^3$) implied the reduced affinity of **1564** to calcium ions, which is identical to the calculated differences in steric and electrostatic properties of **1564** and **1577**. Thus, introduction of the biphenyl linkage to the macrocyclic ring decreased its mobility and this fact might be responsible for the reduction of biological activity (404).

7.11 Cathepsin B and L Inhibitory Activity

A crude extract of *Porella japonica* showed potent inhibitory activity for both cathepsins B and L. Biological activity-guided fractionation of the crude extract gave the three new guaianolides **749–751**, together with porelladiolide (**747**) and its epoxide (**748**). Of these compounds, 11,13-dehydroporelladiolide (**750**) showed weak inhibitory activities against cathepsin B (13.4% at $10^{-5}\ \text{mol}/\text{cm}^3$) and cathepsin L (24.7% at $10^{-5}\ \text{mol}/\text{cm}^3$) (316).

7.12 Cytotoxic and Apoptotic Activity

Several eudesmanolides, germacranolides, and guaianolides isolated from liverworts exhibit cytotoxic activity against KB nasopharyngeal and P-388 lymphocytic leukemia cells (40). The crude ether extracts of the liverworts *Bazzania pompeana*, *Kurzia makinoana*, *Lophocolea heterophylla*, *Makinoa crispata*, *Marsupella emarginata*, *Pellia endiviifolia*, *Plagiochila fruticosa*, *P. ovalifolia*, *Porella caespitans*, *P. japonica*, *P. perrottetiana*, *P. vernicosa*, and *Radula perrottetii* showed cytotoxicity against P-388 cells (IC_{50} value range $4\text{--}20\ \mu\text{g}/\text{cm}^3$). In contrast, crude extracts of *Frullania diversitexta*, *F. ericoides*, *F. muscicola*, *F. tamarisci* subsp. *obscura*, *Lepidozia vitrea*, *Pallavicinia subciliata*, *Plagiochila sciophila*, *Spruceanthus semirepandus*, and *Trocholejeunea sandvicensis* were inactive against this same cell line (IC_{50} values $>20\ \mu\text{g}/\text{cm}^3$) (Asakawa, unpublished results).

$2\alpha,5\beta$ -Dihydroxybornane-2-cinnamate (**64**), from *Conocephalum conicum*, and lunularin (**1477**), from *Dumortiera hirsuta*, exhibited cytotoxic activity against human HepG2 cells, with IC_{50} values of 4.5 and $7.4\ \mu\text{g}/\text{cm}^3$, respectively (487).

An ether extract of *Plagiochila ovalifolia* showed inhibitory activity against P-388 murine leukemia cells, and its constituents, plagiochiline A (**183**), plagiochiline A-15-yl octanoate (**213**), and 14-hydroxyplagiochiline A-15-yl (2*E*,4*E*)-dodecadienoate (**218**), exhibited IC_{50} values of 3.0, 0.05, and 0.05 $\mu\text{g}/\text{cm}^3$, respectively (**888**). Compound **213** and plagiochiline A-15-yl decanoate (**214**) from *P. ovalifolia*, polygodial (**548**) from *P. vernicosa* complex, as well as sacculatal (**1348**) from *P. endiviifolia* showed cytotoxic activity against a human melanoma cell line (IC_{50} value range 2–4 $\mu\text{g}/\text{cm}^3$). Compound **1348** was cytotoxic also for Lu1 (IC_{50} 5.7 $\mu\text{g}/\text{cm}^3$), KB (3.2), LNCaP (7.6), and ZR-75-1 cells (7.6) (Cordell, Pezzuto, Asakawa, unpublished results). Lepidozenolide (**389**) showed potent cytotoxicity when evaluated in the P-388 murine leukemia cell line (IC_{50} 2.1 $\mu\text{g}/\text{cm}^3$) (**746**).

Chandolide (**224**), 13,18,20-tri-*epi*-chandonanthone (**954**), and anadensin (**1105**), obtained from *Chandonanthus hirtellus*, were evaluated for cytotoxic activity against the HL-60 leukemia cell line, and exhibited IC_{50} values, in turn, of 5.3, 18.1, and 17.0 $\mu\text{g}/\text{cm}^3$. 6 α -Methoxyfusicoauritone (**1108**) showed some cytotoxicity against KB cells (IC_{50} 11.2 $\mu\text{g}/\text{cm}^3$), although compounds **954** and **1105** were inactive (**422**, **423**).

Chiloscyphone derivatives, found in *Chiloscyphus rivularis*, were tested against the RS322, RS188N, and RS321 yeast strains. Of these, 13-hydroxychiloscyphone (**447**) showed IC_{12} values of 75 and 88 $\mu\text{g}/\text{cm}^3$ for strains RS321 and RS322. These data are characteristic of a selective DNA-damaging agent that does not act as a topoisomerase I or II inhibitor. Compound **447** also showed cytotoxic activity against lung carcinoma A-549 cells (IC_{50} value 2.0 $\mu\text{g}/\text{cm}^3$) (**956**).

(-)-*ent*-Arbusculin B (**672**) and (-)-*ent*-costunolide (**710**), obtained from *Hepatostolonophora paucistipula*, showed cytotoxic activity against P388 murine leukemia cells, with IC_{50} values of 1.1 and 0.7 $\mu\text{g}/\text{cm}^3$ (**92**). Costunolide (**709**) isolated from *Frullania nisqualensis* showed growth inhibitory activity against the A-549 human lung carcinoma cell line with an IC_{50} value of 12 $\mu\text{g}/\text{cm}^3$ (**410**). The same lactone (**709**) showed moderate, but selective, DNA-damaging activity against the RS321N, RS322YK, and RS167K mutant yeast strains, with IC_{12} values of 50, 150, and 330 $\mu\text{g}/\text{cm}^3$ (**410**). Naviculyl caffeate (**846**), isolated from *Bazzania novae-zelandiae*, gave growth inhibitory effects against P-388 murine leukemia cells with a GI_{50} (concentration that inhibited growth to 50% of control) value of 0.8–1.1 $\mu\text{g}/\text{cm}^3$, although naviculol (**845**) was inactive (**145**). *Riccardia crassa* produces riccardiphenol C (**924**), which showed slight cytotoxicity against BSC-1 (African green monkey kidney epithelial) cells at 60 $\mu\text{g}/\text{disk}$ (**651**).

The ether and methanol extracts of the Tahitian *Mastigophora diclados* showed cytotoxic activity against HL 60 cells at IC_{50} 2.4 and 13.1 $\mu\text{g}/\text{cm}^3$ and KB cells at 14.6 and 32.5 $\mu\text{g}/\text{cm}^3$, respectively (**425**). α -Herbertenol (**509**), (-)-herbertene-1,2-diol (**512**), mastigophorene C (**530**), mastigophorene D (**531**), and (-)-diplophyllolide (**621**) isolated from both extracts mentioned above were cytotoxic for HL 60 cells with IC_{50} values of 1.4, 12.8, 1.4, 2.4, and 2.5 $\mu\text{g}/\text{cm}^3$. They also showed cytotoxicity against KB cells (IC_{50} values of 3.3, 12.5, 11.8, 14.8, and 14.2 $\mu\text{g}/\text{cm}^3$). Diacetate and 2-methoxy derivatives of herbertane-1,2-diol (**512**)

showed evidence of having less potent cytotoxicities than the parent compound against both HL 60 and KB cells. However, (–)-diplophyllin (**676**), a double bond isomer of diplophyllolide (**678**) did not demonstrate cytotoxicity against either of these cell lines (**425**).

Glaucescenolide (**931**) from *Schistochila glaucescens* showed cytotoxic activity against P-388 mouse leukemia cells (IC_{50} 2.3 $\mu\text{g}/\text{cm}^3$) (**712**). *ent*-1 β -Hydroxykauran-12-one (**1166**), isolated from *Paraschistochila pinnatifolia*, and 1 α -hydroxy-*ent*-sandaracopimara-8(14),15-diene (**1328**), from *Trichocolea mollissima*, showed IC_{50} values of 15 and >25 $\mu\text{g}/\text{cm}^3$, when evaluated against this same cell line (**483**).

Fractionation of a cytotoxic ethanol-soluble extract of *Lepidolaena taylorii* (P-388 cell line, IC_{50} 1.3 $\mu\text{g}/\text{cm}^3$), led to the purification of the 8,9-secokaurane diterpenoids, rabdoubrosanin (**1178**), 16,17-dihydorabdoubrosanin (**1179**), 8,14-epoxyabdoubrosanin (**1180**) and **1181–1184**, and the *ent*-kaur-16-en-15-ones, **1142**, **1144**, **1163**, **1185**, and **1186**. In turn, *L. palpebrifolia* also elaborated the 8,9-secokauranes **1178** and **1180**. The cytotoxicity of these *ent*-8,9-*seco* and *ent*-kaurene substances was tested against the mouse P-388 leukemia and several human tumor cell lines, inclusive of six leukemia and a range of organ-specific cancer cell lines. Of the test compounds, **1178** and **1180** showed the most potent cytotoxic activities (mean IC_{50} values of 0.006 and 0.27 $\mu\text{g}/\text{cm}^3$; GI_{50} values of 0.10 and 1.2 μM , respectively). Compound **1179** also showed cytotoxicity against the P-388 cell line at 0.80 μM . Compounds **1178** (including 10% of **1179**) and **1180** showed differential cytotoxicity *in vitro* when tested against five further leukemia cell lines with **1178** showing an average IC_{50} value of 0.4 μM ; however, cell growth was not inhibited by **1180** ($IC_{50} >50$ μM). The growth of seven colon cancer cell lines was inhibited also by **1178** (mean IC_{50} value, 6 μM) (**652**, **654**). Compounds **1178** and **1180** were tested in an *in vivo* hollow fiber model system, in which neither compound was active at the doses tested (18 and 12 mg/kg for **1178** and 150 and 100 mg/kg for **1180**). Compound **1184** was most active against several leukemia cell lines (mean GI_{50} 0.3 μM) and least active against various central nervous system cancer cell lines (mean GI_{50} 6 μM) (**654**). The mode of action for the cytotoxicity of the *ent*-8,9-*secokaur*-16-en-15-one and *ent*-kaur-16-en-15-one series was supported by Michael addition of a thiol to the C-16–C-17 double bond of **1178**, but the C-8–C-14 double bond of **1179** was relatively unreactive (**652**, **654**).

A new atisane-2 derivative (**1414**) from *Lepidolaena clavigera* showed weak inhibitory activity against mouse lymphocytic leukemia cells (P-388) with an IC_{50} value of 16 $\mu\text{g}/\text{cm}^3$ (**655**). α -Zeirin (**1437**) has been isolated from several liverworts and displayed cytotoxic activity against P-388 cells with an IC_{50} of 1.1 $\mu\text{g}/\text{cm}^3$ (**619**, **944**).

The crude ether extract of two unidentified Indonesian and Tahitian *Frullania* species exhibited cytotoxic activity against both the HL-60 and KB cell lines, with EC_{50} values of 6.7 and 1.6 $\mu\text{g}/\text{cm}^3$ (HL-60 cells) and 1.6 and 11.2 $\mu\text{g}/\text{cm}^3$ (KB cells), respectively (**426**). Bioactivity-guided fractionation of the Indonesian sample led to the isolation of (+)-3 α -(4'-methoxybenzyl)-5,7-dimethoxyphthalide

(**1807**), (–)-3 α -(3'-methoxy-4',5'-methylenedioxybenzyl)-5,7-dimethoxyphthalide (**1814a**), together with 3-methoxy-3',4'-methylenedioxybibenzyl (**1487**), 2,3,5-trimethoxy-9,10-dihydrophenanthrene (**1772**), atranorin (**1838**), and lichexanthone (**1851a**), among which **1807** possessed the most potent cytotoxic activity against HL-60 and KB cells showing IC_{50} values of 0.92 and 0.96 μM . The other compounds (**1487**, **1772**, **1814a**) and the 6'-nitro derivative of **1487** indicated much less activity against both cell lines (HL-60 IC_{50} value range, 6.3–96.6 μM ; KB IC_{50} value range, 5.5–124.3 μM). From the Tahitian sample, costunolide (**709**) and tulipinolide (**712**) were obtained and the latter germacranolide shown to be cytotoxic against the HL-60 cell line (IC_{50} value 4.6 μM) (**426**).

The ether extract of the Japanese *Porella perrottetiana* also showed cytotoxicity against both HL-60 and KB cell lines (**426**). The same treatment as mentioned above gave 4 α ,5 β -epoxy-8-*epi*-inunolide (**714**), 7-keto-8-carbomethoxypinguisenol (**848**) and perrottetianal A (**1354**). The former two compounds exhibited moderate or weak cytotoxicity against HL-60 (IC_{50} 8.5 and 2.7 μM) and KB cells (IC_{50} 52.4 and 46.3 μM). 7 α -Hydroxy-8-carbomethoxypinguisenol and acutifolone A (**849**) prepared from **848** by reduction and dehydration were evaluated against HL-60 (IC_{50} 83.10 and >177 μM) and KB cells (IC_{50} 2.7 and 46.6 μM). It was suggested that the dienone group plays an important role in the mediation of cytotoxicity against HL-60 cells (**426**).

Neomarchantins A (**1595**) and B (**1596**), marchantin C (**1579**), and a mixture of sesquiterpene/bis-bibenzyl dimers, GBB A (**1658**) and GBB B (**1659**) from *Schistochila glaucescens* showed growth inhibitory effects for the P-388 cell line, with IC_{50} values of 18, 7.6, 8.5, and 10.3 $\mu g/cm^3$, respectively (**712**).

The thalloid liverwort, *Marchantia polymorpha*, which can cause allergic contact dermatitis, is also known to exhibit inhibitory activity against Gram-positive bacteria, and has diuretic activity (**39**, **40**). The methanol extract (105 g) of a Japanese specimen of *M. polymorpha* was chromatographed over silica gel and Sephadex LH-20 to give the cyclic bis-bibenzyls, marchantin A (**1577**) (30 g), and its analogues, **1578–1582**, **1585**, and **1595**. The yield of **1577** is dependent upon the particular *Marchantia* species being investigated. Pure **1577** (80–120 g) has been isolated from 6.67 kg of dried *M. paleacea* var. *diptera*. This thalloid liverwort elaborates not only compounds of the marchantin series, including marchantins A (**1577**), B (**1578**), D (**1580**), and E (**1581**), but also the acyclic bis-bibenzyls, perrottetin F (**1639**) and paleatin B (**1642a**) (*Asakawa, unpublished results*). Marchantins A (**1577**), B (**1578**), D (**1580**), perrottetin F (**1639**), and paleatin B (**1642a**) showed DNA polymerase β inhibitory (IC_{50} range 14.4–97.5 μM), cytotoxicity against KB cells (IC_{50} range 3.7–20 μM), and anti-HIV-1 activity (IC_{50} range 5.3–23.7 $\mu g/cm^3$) (**84**, **85**).

Marchantin A (**1577**) induced cell growth inhibition in human MCF-7 breast cancer cells at IC_{50} 4.0 $\mu g/cm^3$. Fluorescence microscopic and a Western blot analysis indicated that compound **1577** actively induced apoptosis of MCF-7 cells through a caspase-dependent pathway. The phenolic hydroxy groups at C-1' and C-6' are responsible for inducing cytotoxic and antioxidant activity (**355**).

Riccardin D (= plagiochin E) (**1567**) indicated antiproliferative activity on human glioma A172 cells and induction of apoptosis at 16 μM . Compound **1567** also possesses potent effects in reversing P-glycoprotein-mediated multidrug resistance (**737**).

Blasia pusilla produces the bis-bibenzyl dimers, pusilatins A-D (**1652–1655**). Pusilatins B (**1653**) and C (**1654**) were found to possess DNA polymerase β inhibitory activity (IC_{50} values of 13.0 and 5.16 μM , respectively), growth inhibitory effects on KB cells (ED_{50} values of 13.1 and 13.0 $\mu\text{g}/\text{cm}^3$) and weak HIV-RT inhibitory activity (**971**). 2-Hydroxy-3,4,6-trimethoxyacetophenone (**1720**) and 2-hydroxy-4,6-dimethoxyacetophenone (**1721**), isolated from *Plagiochila fasciculata*, were inactive against the P-388 cell line (IC_{50} values of $>50 \mu\text{g}/\text{cm}^3$) (**481**).

Trichocolea lanata and *T. tomentella* produce tomentellin (**1748**), which showed inhibitory activity against African green monkey kidney epithelial (BSC-1) cells at 15 $\mu\text{g}/\text{cm}^3$, with no antiviral effects against herpes simplex or polio viruses. Demethoxytomentellin (**1752**) isolated from *Trichocolea tomentella* showed a similar cell growth inhibitory effect, indicating that both an allylic ether and a conjugated enone substructure are required for such activity (**653**). Methyl-4-[(2*E*)-3,7-dimethyl-2,6-octadienyl]oxy-3-hydroxybenzoate (**1754**), isolated from *Trichocolea hatcheri*, showed a lack of cytotoxicity ($IC_{50} > 100 \mu\text{M}$) against both KB and SK-MEL-3 human melanoma cells, as well as NIT 3T3 fibroblasts (**93**).

The *ent*-kauranes **1158** and **1203–1205** isolated from *Jungermannia* species inhibited HL-60 cells with IC_{50} values, in turn, of 0.49, 7.0, 0.59, and 0.28 μM . Treatment of **1158** and **1203–1205** caused proteolysis of poly(ADP-ribose) polymerase, a sign of activation of the apoptotic machinery, whereas the feature of cell death induced by treatment with compounds **1203** and **1204** was necrosis. Treatment with compound **1205** induced apoptosis (see below) (**602**). The *ent*-kaurane diterpenoids **1155**, **1161**, and **1206–1208** from a *Jungermannia* species showed cytotoxicity for HL-60 cells with IC_{50} values of 1.00, 0.40, 1.21, 1.28, and 0.78 μM , respectively (**609**).

The *ent*-kaurenes **1158**, **1160**, **1165**, and **1199–1202**, isolated from the Japanese liverwort *Jungermannia truncata*, were evaluated for cytotoxicity against HL-60 human leukemia cells. Of these, *ent*-11 α -hydroxy-16-kauren-15-one (**1158**) induced apoptosis (programmed cell death) in this cell line partly through a caspase-8 dependent pathway (**601**). The presence of an enone group in this class of molecule appears to be essential for the induction of apoptosis and the activation of caspases in human leukemia cell lines (**427–429**, **602**).

ent-Kaurenes **1143**, **1144**, and **1158**, *ent*-9(11),16-kauradien-12,15-dione (**1204**), and the rearranged *ent*-kaurene, jungermannenone A (**1205**), selectively inhibited nuclear factor- κB (NF- κB)-dependent gene expression due to treatment with TNF- α . Compound **1158**, in combination with TNF- α , caused a dramatic increase in apoptosis in human leukemia cells accompanied by activation of caspases. Compound **1158**, when combined with camptothecin, also caused an increase in apoptosis (**787**, **788**). Jungermannenones A-D (**1205–1208**), obtained from *Jungermannia* species, induced cytotoxicity against human leukemia HL-60 cells at 50% inhibitory concentrations of 1.3, 5.5, 7.8, and 2.7 μM , respectively, and DNA fragmentation and nuclear

condensation. Both are biochemical markers of apoptosis induction, and apoptosis was induced through a caspase-independent pathway. Compounds **1205** and **1208** showed inhibitory activity for NF- κ B, which is a transcriptional factor of antiapoptotic factors. Thus, *ent*-kaurene diterpenoids from liverworts may be promising candidates as antitumor agents (428, 429).

Some monoterpenoids, such as (–)-bornyl acetate (**58**) demonstrate potent apoptosis-inducing activities against the cultured cells of *Marchantia polymorpha*. Apoptosis induced by monoterpenoids occurs *via* the production of active oxygen species such as H₂O₂ (370).

The ursane triterpenoids from the liverwort *Ptilidium pulcherrimum*, ursolic acid (**1467**), 2 α ,3 β -dihydroxyurs-12-en-28-oic acid (**1469**) and acetoxursolic acid (**1468**), showed inhibition of the growth of PC3 human prostate cancer cells, at concentrations between 10.1 $\pm$ 1.00 and 39.7 $\pm$ 2.98 μ M (271).

Pallidisetin A (**2088**) and pallidisetin B (**2089**), isolated from the moss *Polytrichum pallidisetum*, showed cytotoxicity against human melanoma (RPMI-7951) and human glioblastoma multiforme (U-251 MG) cells, with ED₅₀ values of 1.0 and 1.0 μ g/cm³ and 2.0 and 2.0 μ g/cm³ (984).

Three cytotoxic compounds, 1-*O*-methylohoensin B (**2102**), 1-*O*-methyldihydrohoensin B (**2103**) and 1,14-di-*O*-methyldihydrohoensin B (**2104**) were isolated from *Polytrichum pallidisetum*. Compound **2102** proved to be cytotoxic for human colon adenocarcinoma (HT-29), human melanoma (RPMI-7951), and human glioblastoma multiforme (U-251 MG) cells, with ED₅₀ values of 1.0, 1.0, and 2.0 μ g/cm³. Compound **2103** showed inhibitory activity only against U-251 cells (ED₅₀ 0.8 μ g/cm³) while **2104** inhibited the growth of the A549 lung carcinoma (A549) (ED₅₀ 1.0 μ g/cm³) and RPMI-7951 melanoma (ED₅₀ 1.0 μ g/cm³) cell lines (984). Ohioensin H (**2106**) from *Polytrichum commune* did not show any cytotoxicity against the five human cancer cell lines in which it was evaluated (IC₅₀ in all cases >5 μ g/cm³) (233).

Marchantin C (**1579**) and its dimethyl ether, 7,8-dehydro-marchantin C and its dimethyl ether were synthesized and their possible modulatory effects on P-glycoprotein in VCR-resistant KB/VCR cells were investigated (965). The results indicated that **1579** was the most potent inhibitor of cell proliferation in both KB and KB/VCR cells among these four synthetic compounds, while the three derivatives of **1579** has little antiproliferative activity. Potent apoptosis in KB/VCR cells was induced by treatment with 16 μ M of dimethyl ether of marchantin C (**1579**) and 0.2 μ M VCR for 48 h (965).

7.13 Farnesoid X-Receptor (FXR) Activation

The farnesoid X-receptor (FXR), a member of the nuclear-receptor super-family, controls the expression of critical genes in bile acid and cholesterol homeostasis. Marchantins A (**1577**) and E (**1581**) activated FXR in this receptor-binding assay at

a high potency level, comparable to that of the most potent endogenous bile acid, chenodeoxycholic acid (794).

7.14 α -Glucosidase Inhibitory Activity

Inhibitory activity of α -glucosidase is associated with antiobesity and antidiabetes. Among bis(benzyls) found in liverworts, only marchantin C (1579) thus far has shown inhibitory activity against α -glucosidase (52.2% at 1 mM). This activity is lower than that of the 1-deoxynojirimycin (100% at 0.4 mM). This is the first report on the α -glucosidase inhibitory activity of macrocyclic bis-benzyls (295).

7.15 Insecticidal Activity

Lepidolaena hodgsoniae biosynthesizes hodgsonox (758), which showed weak insecticidal activity against the larvae of the Australian green blowfly *Lucilia cuprina*, with a LC_{50} value of 270 $\mu\text{g}/\text{cm}^3$, and was less active than the standard insecticide, diazinon (LC_{50} 1.6 $\mu\text{g}/\text{cm}^3$) (22). Atisane 2 (1414), obtained from *Lepidolaena clavigera*, showed moderate insecticidal activity against blow fly larvae (655). Metacalypogin (1823), from *Metacalypogeia alternifolia*, inhibited the metamorphosis of *Oncopeltus fasciatus*, with four out of 30 insects in total never reaching adulthood (748).

7.16 Liver X Receptor Alpha (LXR α) Agonist Activity

Riccardin C (1566) isolated from *Blasia pusilla* possesses a nuclear receptor LXR α selective agonist activity (990). Thus, riccardin C (1566) and its seven *O*-methyl derivatives, including riccardins A (1564) and F (1568), were synthesized. According to a preliminary structure-activity relationship study of these seven *O*-methylated riccardins, the three phenolic hydroxy groups of riccardin C were determined as being indispensable for binding to the LXR α receptor (342).

7.17 Muscle Relaxant Activity

Marchantin A (1577) and its trimethyl ether have shown muscle-relaxant activity (797). MM2 calculations indicated that this pharmacologically interesting phenomenon was attributable to the structural similarity between 1577 and a well-known skeletal muscle relaxing agent, the bis-benzylisoquinoline alkaloid,

tubocurarine (797). Keseru and Nogradi have pointed to a structural similarity between marchantin A (1577) and the therapeutically important bis-benzylisoquinoline alkaloid, cepharathine (402). They predicted that the similar therapeutic properties of 1577 and cepharathine could be attributed to their binding on a common receptor. Included were antibacterial activity against Gram-negative and -positive bacteria and against human H37Rv *Mycobacterium tuberculosis*, *M. avium* and *M. nocardia*, cytotoxic activity against various human and murine cancer cells, and the inhibition of 5-lipoxygenase and calmodulin. The wide range of biological activities of marchantin A (1577) also could be interpreted by a mechanism of action based on calcium-ion binding.

7.18 Nematode Larval Motility Inhibition Activity

An *in vitro* nematode larval motility inhibition assay has been developed to screen liverwort extracts for anthelmintic activity against third-stage larvae of the sheep parasite, *Trichostrongylus colubriformis*. 3-Methoxy-4'-hydroxybibenzyl (1482), isolated from the New Zealand liverwort, *Plagiochila stephensoniana*, showed activity against this nematode, with an IC_{50} value of 0.13 mg/cm³. Polygodial (548), isolated from the pungent-tasting higher plant, *Pseudowintera colorata* or the liverwort *Porella vernicosa* complex (40), showed improved activity (IC_{50} 0.07 mg/cm³) when compared with compound 1482. Synthetic (Z)- and (E)-3-methoxy-4'-hydroxystilbenes (1484) gave IC_{50} values of 0.06 and 0.07 mg/cm³, respectively, in this same bioassay. The synthetic 3,4'-dimethoxybibenzyl (1501) displayed a reduced activity (30% inhibition at 0.7 mg/cm³) as compared to 1482 (85% inhibition at 0.6 mg/cm³) (482).

7.19 Neuroprotective Activity

Mastigophorenes A (528) and B (529) from *Mastigophora diclados* showed a significant neuroprotective effect on neuronal survival at 1 μ M in primary cultures of fetal rat cortical neurons, in addition to neuronal out-growth promoting activity (240).

7.20 Nitric Oxide Production Inhibition

Over-production of nitric oxide (NO) is involved in inflammatory response-induced tissue injury and the formation of carcinogenic *N*-nitrosamines (10). Large amounts of NO are expressed and generated by induced inducible nitric oxide synthase (iNOS) on stimulation of endotoxins or cytokines involved in pathological

Table 7.1 NO production inhibitory activity of herbertane and its dimers and cuparenes isolated from *Mastigophora diclados*

Compounds	NO inhibition $IC_{50}/\mu M$
1,2-Cuparenediol (487)	9.2
2-Hydroxy-4-methoxycuparene (492)	4.1
α -Herbertenol (509)	76.0
Herbertene-1,2-diol (512)	8.03
β -Herbertenol (511)	12.23
1,2-Dihydroxyherberten-12-al (517)	34.0
1,2-Diacetate of 512	7.01
Mastigophorene C (530)	10.18
Mastigophorene D (531)	15.16
L-(N ₆ -Iminoethyl)lysine	18.6

responses. Thus, inflammatory disease will be induced by over-production of NO by iNOS. Accordingly, finding new agents that inhibit NO production from natural sources is important in drug discovery.

The herbertane monomers **509**, **511**, and **512**, their dimers **530** and **531**, isolated from *Mastigophora diclados*, and the cuparenes **487** and **492** from *Bazzania decrescens*, showed inhibition of lipopolysaccharide (LPS)-induced production of nitrite, and their IC_{50} values are reported in Table 7.1. Potent inhibition was observed for the herbertanes and cuparenes if hydroxy groups are located at *meta* and/or *para* positions to C-12. An aromatic methyl group seems to be important for this type of inhibition, and oxidation of the aromatic methyl to a formyl group decreased the inhibition of NO production (296). Myltayl-4(12)-enyl-2-cafeate (**818**) from *Bazzania nitida* displayed a potent inhibition of NO production with an IC_{50} value of 6.3 μM (289).

Norpinguisone (**860**), norpinguisone methyl ester (**861**) and *ent*-16-kauren-15-one (**1144**) isolated from *Porella densifolia* showed inhibitory activity against NO production in LPS stimulated RAW 264.7 cells at IC_{50} 45.5, 1.7 and 69.4 μM , respectively (669).

Clerodanes **985** and **986**, from *Thysananthus spathulistipus*, and bibenzyl derivatives **1512**, **1516**, **1519**, **1530**, **1534**, and **1535**, from *Radula appressa*, were tested for inhibition of NO production in the cultured RAW 264.7 cells in response to lipopolysaccharide (LPS). All of the bibenzyls inhibited NO production in LPS-stimulated RAW 264.7 cells at a 50% inhibitory concentrations in the range 4.5–20 μM , with the best activity shown by 2-geranyl-3,5-dihydroxybibenzyl (**1530**). This type of activity was suggested to be due to the antioxidant properties of these test compounds (294).

The inhibition of lipopolysaccharide (LPS)-induced NO production in cultured RAW 264.7 cells by macrocyclic bis-bibenzyls isolated from several liverworts has been evaluated, and the IC_{50} values of these compounds are shown in Table 7.2.

Concerning the structural requirements for the potent inhibition of NO production by bis-bibenzyls, the presence of C-1,C-2' and C-14,C-11' diaryl ether bonds seems to be important. The occurrence of phenolic hydroxy groups also plays an important role in mediating this type of inhibitory activity. Compounds with a C-7,

Table 7.2 NO production inhibitory activity of bis-benzyls isolated from liverworts

Compounds	NO inhibition $IC_{50}/\mu M$
Riccardin A (1564)	2.50
Riccardin C (1566)	> 100
Riccardin F (1568)	5.0
Marchantin A (1577)	1.44
Marchantin B (1578)	4.10
Marchantin D (1580)	10.18
Marchantin E (1581)	62.16
Perrottetin F (1639)	7.42
Marchantin A trimethyl ether ^a	42.50
Marchantin B trimethyl ether ^a	42.45

^aDerivatives from marchantin A (**1577**) and marchantin B (**1578**)

C-8 unsaturation show dramatically decreased inhibition of NO, while introduction of a hydroxy group at C-7' results in slightly decreased activity. The methyl ethers of marchantin A (**1577**) and marchantin B (**1578**) showed weaker activity than the parent compounds (292).

7.21 Plant Growth Inhibitory Activity

Yoshikawa and associates reported that lunularic acid (**1478**) inhibited germination and growth of cress (*Lepidium sativum*) and lettuce (*Lactuca sativa*) at 1 mM and gibberellic acid-induced α -amylase induction in embryo-less barley seeds at 120 μM , which has been recognized as a specific activity of abscisic acid (ABA) (975). Both **1478** and ABA equally inhibited the growth of the liverwort *Lunularia cruciata* strain callus at 40 and 129 μM . Superimposition between the stable conformers of **1478** and those of ABA obtained by computational analysis (MM calculations) has been used to explain why **1478** has an ABA-like activity in higher plants. This indicates that both **1478** and ABA bind to the same receptor. On the basis of the distribution pattern of **1478** and ABA, a hypothesis has been proposed that higher plants have altered their endogenous growth regulator from **1478** to abscisic acid in their evolutionary process (975).

7.22 Piscicidal Activity

Pellia endiviifolia is known to produce a large amount of sacculatane diterpenoids with its crude extract found to be very toxic against fish (40). The piscicidal activities of sacculatals **1348**–**1351** and **1363**–**1372** were tested against killifish, among which only sacculatal (**1348**) and 1 β -hydroxysacculatal (**1350**) were lethal within 20 min at a concentration of 1 ppm, indicating that both the 8- and 9 β -diformyl groups present in these molecules were responsible for such activity (311).

7.23 Tubulin Polymerization Inhibition

Marchantin C (**1579**) strongly inhibited the growth of human cervical tumor xenografts in nude mouse and decreased the quantity of microtubules in a time- and dose-dependent manner at the G2/M phase in human glioma tumor cells and HeLa (human cervical adenocarcinoma cell line) cells at 8–16 μM . Marchantin C (**1579**) decreased the polymerization rate of gross tubulin, similar to the microtubule depolymerizer, vincristine, at 8–24 μM . These results indicated that marchantin C (**1579**) plays the same role in microtubule depolymerization in both its apoptotic effects in the cell and subsequent antitumor activity *in vivo*. Marchantin C (**1579**) is a novel microtubule inhibitor that induces mitotic arrest of tumor cells and suppresses tumor cell growth. The structure of marchantin C is distinct from classical microtubule inhibitors like colchicine, paclitaxel, vinblastine, and vincristine. However, this macrocyclic bisbibenzyl may be regarded as a potential antitumor agent as a result of inhibiting microtubule polymerization (738, 739).

Isoplagiochins A (**1604**) and B (**1605**) isolated from *Plagiochila fruticosa* inhibited the polymerization of tubulin with IC_{50} values of 50 and 25 μM . The dihydro derivatives of both **1604** and **1605** were found to be inactive ($IC_{50} > 100 \mu\text{M}$), and, when compared with the parent compounds, indicated that a restricted biaryl ring system is favorable for tubulin binding. A Monte Carlo search showed that the presence of two aromatic rings connected by a two-carbon bridge with a double bond may serve to maintain the backbone conformation (553).

7.24 Vasorelaxation

Lepidozenolide (**389**) and (–)-5 β -hydroperoxylepidozenolide (**390**) have been found to cause vasorelaxation of the rat thoracic aorta, in terms of phasic and tonic contractions induced by norepinephrine (3 μM), when evaluated at a 100 $\mu\text{g}/\text{cm}^3$ concentration. Compound **389** also inhibited potassium- (80 μM) and calcium- (1.9 μM) induced vasoconstriction (746).

8 Chemosystematics of Marchantiophyta

On the basis of morphological characteristics, liverworts have been divided into the Marchantioid group or “complex thalloids”, and the Jungermannioid group, which comprises two morphological subgroups, “simple thalloids” and “leafy hepatics”. These groups have been defined in the hierarchy of most classification schemes and have long been viewed as natural phylogenetic units (167, 732). Recent molecular phylogenetic studies have brought new insights to the systematics of liverworts and have greatly modified this morphology-based concept (337, 665). The new classification of the Marchantiophyta proposed by *Crandall-Stotler* and coworkers (168, 169) is presented in Table 1.1 (see page 5). Each underlined genus has been studied chemically previously.

One of the outstanding features of plants, in addition to their form, is their chemistry. All liverworts are morphologically very small and their identification is very difficult. Species are still distinguished primarily by their appearance, but it is becoming very clear that appearance alone does not necessarily define whether two organisms are different from each other.

Liverworts are characterized by the presence of oil bodies (see Fig. 17, page 5), unique organelles in which terpenoids and aromatic compounds are accumulated (227, 785). Although the function of the oil bodies is still controversial, these single-membrane-bound organelles are restricted to liverworts and occur in approximately 90% of these taxa (732). Many different types of oil bodies have been described and/or illustrated, and are sometimes used to organize taxonomic units. Variations that occur in oil body size, shape, color, number, and distribution are informative characteristics for liverworts taxonomically (167, 723, 724). Terpenoids and aromatic metabolites, which occur in the oil bodies of the Marchantiophyta, are also of value for taxonomic investigations. A survey of the scientific literature allows one to locate papers concerning the chemosystematics of liverworts in general (39, 40, 45) as well as the chemosystematics of liverwort families or genera (75, 81, 264, 490, 495, 689, 698). Secondary metabolites, such as lipophilic terpenoids and aromatic compounds that accumulate in cellular oil bodies can assist in liverwort taxonomic differentiation. Knowledge of the chemical constituents of liverworts might serve to delineate not only chemical, but also

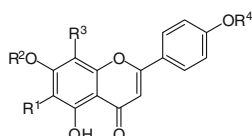
evolutionary relationships within the Marchantiophyta at the genus or family level. Up to the present, more than 1,000 species of liverworts have been collected and chemically investigated, especially from Japan, Germany, Malaysia, New Zealand, the U. K., and several other countries. Many kinds of detected and isolated compounds can be used as taxonomic indicators of each species of the Marchantiophyta.

In the following sections of this chapter, the chemosystematics of the liverworts will be described, from the viewpoint of the taxonomic classification of these plants.

8.1 Chemosystematics of Haplomitriopsida

The Haplomitriopsida class of the liverworts is species poor in comparison to the other two classes, with seven species in *Haplomitrium*, seven in *Treubia* and four in *Apotreubia* (169). Among these, only *Haplomitrium* has been analyzed chemically.

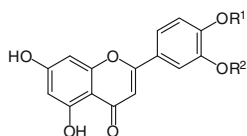
The genus *Haplomitrium* is considered to be a very primitive taxon. From the Japanese *H. mnioides*, phytanes and complex labdane-type diterpenoids have been isolated (40). The New Zealand liverwort *H. gibbsiae* contains three major flavonoid glucosides: apigenin 7-*O*-glucoside (1915), apigenin 7,4'-di-*O*-glucoside (2184), and isoscutellarein 7-*O*-glucoside (2185). All of these flavonoids are thought to contain at least one acyl group per sugar (507). Acylated flavonoids are very rare among liverworts. Up to the present, acylated apigenin 7-*O*-glucuronides have been detected in *Riccia crystallina* (Ricciaceae) (519) and apigenin 6-*C*-arabinoside-8-*C*-(2''-*O*-ferulyl) glucoside (2186) in *Metzgeria conjugata* (829).



2184 R¹=R³=H, R²=R⁴=Glc (apigenin-7,4'-di-*O*-glucoside)

2185 R²=Glc, R¹=R⁴=H, R³=OH (isoscutellarein-7-*O*-glucoside)

2186 R¹=Ara, R²=R⁴=H, R³=(2''-*O*-ferulyl)Glc;
(apigenin 6-*C*-arabinoside-8-*C*-(2''-*O*-ferulyl)glucoside)



2187 R¹=R²=GlcA (luteolin 3',4'-di-*O*-β-D-glucuronide)

Flavonoids found in *Haplomitrium gibbsiae* and *Lunularia cruciata*

Recent cladistic analyses of nuclear, mitochondrial, and plastid gene sequences place this monophyletic group as the basal sister group to all other liverworts (337, 665). However, the diterpenoid and flavonoid constituents of *Haplomitrium* species show a degree of biochemical advancement unexpected in a primitive order.

This genus is chemically more advanced than the genera of Balantiopsidaceae and Herbertaceae in the order Jungermanniales.

8.2 Chemosystematics of Marchantiopsida

8.2.1 Order Blasiales

8.2.1.1 Blasiaceae

The Blasiaceae is a family of the liverworts with only two species: *Blasia pusilla* and *Cavicularia densa*. Both species are chemically isolated from other thalloid liverworts. *B. pusilla* biosynthesizes characteristic cyclic bis-bibenzyl dimers, pusilatin A-D (1652–1655) along with riccardin C (1566), riccardin F (1568), lunularin (1477), lunularic acid (1478), and dehydroresveratrol (1481) (971). It also elaborates phenolic compounds (1729, 1736, 1859, 1860), which have been isolated from various lichens (359). *C. densa* produces (+)-cavicularin (1560) possessing a cyclic bibenzyl-dihydrophenanthrene skeleton (875). Cavicularin (1560) may arise by intramolecular phenolic oxidative coupling of riccardin C (1566). On the other hand, pusilatin A-D (1652–1655), occurring in *B. pusilla*, are formed by intermolecular coupling between two riccardin C (1566) molecules. These riccardin C derivatives are significant chemical markers of the Blasiaceae.

Blasia pusilla is chemically close to *Ricciocarpos natans* (Ricciaceae) which also belongs to the marchantioid group, since the latter species produces pusilatin B (1653) (453). Bis-bibenzyl dimers are very rare compounds. Besides the above-mentioned pusilatin A-D, three more compounds are known, namely, pusilatin E (1656) (a riccardin A dimer) isolated from *Riccardia multifida* subsp. *decrescens* (Aneuraceae) (972), 13',13'''-bis(10'-hydroxyperrottetin E) (1657) from *Pellia epiphylla* (Pelliaceae) (182), and cruciatin (1659a) (a perrottetin F dimer) from *Lunularia cruciata* (Lunulariaceae) (40). Among all these compounds, the only dimers occurring in *B. pusilla* and *R. natans* are riccardin C derivatives. According to the new classification of the liverworts, as presented in Table 1.1, the Blasiaceae family has been separated from the order Metzgeriales (simple thalloid liverworts) and placed into the new order Blasiales within the complex thalloid hepatics. Chemical analysis has supported this new classification.

8.2.2 Order Sphaerocarpaceae

The order Sphaerocarpaceae is subdivided into two families: Sphaerocarpaceae and Riellaceae. *Sphaerocarpos* and *Riella* species mainly produce flavonoid glycosides.

The major flavonoids from *S. texanus* are luteolin 7-*O*-glucuronide (**1895**) and 7,4'-di-*O*-glucuronide (**1895a**). *R. affinis* contains apigenin (**1914**), chrysoeriol, and luteolin (**1895**) 7-*O*-glucuronides. These compounds and luteolin 3'-*O*-glucuronide (**1897**) are produced by *R. americana* (**514**). Lunularin (**1477**) and lunularic acid (**1478**) have been detected in *S. michelii* (**39**). All of the above-mentioned constituents have been isolated from many liverworts of the Marchantioid group such as *Dumortiera hirsuta*, *Monoclea forsteri*, *Marchantia tosona*, and *Marchantia palmata*. Complex thalloid liverworts are known for the presence of flavone *O*-glucuronides in comparison with the simple thalloid hepatics, which produce flavone *C*-glycosides (**509**). These data are in agreement with placement of Sphaerocarpaceae as a part of the Marchantiopsida.

8.2.3 Order Lunulariales

8.2.3.1 Lunulariaceae

Lunularia cruciata is the only species of the genus *Lunularia*. In the new classification of the liverworts, the family Lunulariaceae was transferred from the order Marchantiales and placed into the new order Lunulariales. Among sesquiterpenoids such as β -elemene (**283**), cuparene (**464**), 2-cuparenol (**483**), β -eudesmol (**601**) or (*E*)-nerolidol (**687**), the New Zealand *L. cruciata* produces also lunularin (**1477**) and lunularic acid (**1478**) (**72**). From the Japanese species, the acyclic bis-bibenzyl perrottetin F (**1639**), its 7,8-dehydro derivative (**1641**), and their dimer, cruciatin (**1659a**), have been isolated (**40**). This liverwort is also known for the presence of flavonoids. Luteolin 3',4'-di-*O*- β -D-glucuronide (**2187**), luteolin 3'-*O*- β -D-glucuronide (**1897**) (**39**), and also luteolin 7-*O*- β -D-glucopyranoside (**1899**) and quercetin (**1920**) (**371**) have been detected.

Due to the presence of perrottetin F-type compounds, *L. cruciata* is chemically distinct from liverworts belonging to the order Marchantiales, since these produce mainly marchantin- and riccardin-type bis-bibenzyis (Marchantiaceae) or do not elaborate any bis-bibenzyis (Conocephalaceae) (**40**, **45**). Perrottetin F (**1639**) is a compound previously isolated from leafy liverworts such as *Radula kojana*, *Radula perrottetii*, and *Frullania convoluta* (**40**). The last-mentioned species produces also 7',8'-dehydroperrottetin F (**1641**) (**226**).

8.2.4 Order Marchantiales

8.2.4.1 Aytoniaceae

The Aytoniaceae family comprises five liverwort genera, *Asterella* (Fig. **8.1**), *Cryptomitrium*, *Mannia*, *Plagiochasma*, and *Reboulia*. The genus *Asterella* is the



Fig. 8.1 *Asterella crassa*. (Permission for the use of this figure has been obtained from Mr. Masana Izawa, Saitama, Japan)

second largest genus of Marchantiales (after *Riccia*) with approximately 80 species and almost worldwide distribution (479). *Asterella* species are known to emit intense, characteristic scents, both pleasant and unpleasant (71). *A. echinella* produces mainly sesquiterpenes. It elaborates the sesquiterpene hydrocarbons β -barbatene (235), β -caryophyllene (426), β -acoradiene (69), α -barbatene (234), isobazzanene (260), and δ -cuprenene (468), and also significant amounts of the sesquiterpene alcohol 4 β -hydroxygermacra-1(10),5-diene (702). This species is different chemically from *A. venosa* since the major constituents of *A. venosa* are monoterpenoids. The main compound to have been obtained is geranyl acetate (9), together with β -myrcene (1), α -pinene (47), and myrtenyl acetate (52) (492). This Mexican species is closely related to the Portuguese *A. africana*. Chemical analysis of the essential oil from *A. africana* indicated a predominance of the monoterpene fraction. Myrtenyl acetate (52) and α -pinene (47) were the major components of all the oil samples (222). The Chinese *A. angusta* biosynthesizes cyclic bis-bibenzyls (666). Asterelin A (1597), asterelin B (1598), dihydroptychantol (1600), perrottetin E (1638), the marchantin-type compounds, marchantin H (1583), M (1587), P (1591), 11-*O*-demethylmarchantin I (1599), and the riccardin-type compounds, riccardin B (1565) and D (1567), all have been isolated from this species. *A. blumeana* and *A. tenera* are known for the presence of hopane-type triterpenoids. Diplopterol (1436), α -zeorin (1437) and hop-22,29-diol (1438) have been detected in *A. blumeana* (619). Besides diplopterol (1436), *A. tenera* also produces diploptene (1435) (72).

The liverwort *Reboulia hemisphaerica* has at least three chemotypes, the: (I) atistolane (889), (II) cyclomyltaylane-bis-bibenzyl (242, 935), and

(III) gymnomitrane-cuparane types (492, 929). A liverwort belonging to the aristolane chemotype has been found only in Japan and produces *ent*-aristol-9-en-8 α -ol (112) as the main component, together with other aristolanes (110, 111, 113). Two other chemotypes also have been found in Japan (242, 492). The Taiwanese *R. hemisphaerica*, which belongs to the second chemotype, produces cadinane-type sesquiterpenoids (359–362) besides cyclomylytaylanes and bis-bibenzyls (935). This may be compared with the Japanese species, which elaborates chamigrane sesquiterpenoids (436, 438, 439) (242, 492). Among bis-bibenzyls, the Taiwanese *R. hemisphaerica* produces marchantin C (1579) and marchantins M-O (1587–1590) (935); from the Japanese species riccardin C (1566) was isolated (54). The European species resembles chemically the Japanese third chemotype since it biosynthesizes gymnomitranes and cuparanes, such as (–)-gymnomitr-3(15),4-diene (236), (+)-gymnomitrol (240), (+)-gymnomitr-3(15)-en-4-one (247), cuparene (464), (–)- α -cuprenene (466), and (–)- δ -cuprenene (468) (929).

Mannia fragrans is similar chemically to *R. hemisphaerica* as a result of producing cuparane-type sesquiterpenoids (468, 476–479) (542) and the neomarchantin-type macrocyclic bis-bibenzyl, pakyonol (1601) (45). Pakyonol (1601) has been also isolated from *Plagiochasma pterospermum* together with riccardin C (1566), α -zeorin (1437), and the gymnomitrane-type sesquiterpenoids 235, 243, 244, 247, and 248 (314). Riccardin- and the marchantin-type bis-bibenzyls 1566 and 1571 and 1578 and 1586, together with the hopane triterpenoids 1436, 1437, and 1442, have been found in the Argentinean *P. rupestre* (97). The Japanese *P. japonica* is similar chemically to *P. pterospermum*. The major components of *P. japonica* are riccardin C (1566) and α -zeorin (1437), which have also been detected in *P. pterospermum* (459).

The Pakistani *P. appendiculatum* produces (–)- β -caryophyllene (426), (–)- β -caryophyllene oxide (428) and the marchantin series, marchantins A (1577), B (1578), and C (1579) (861). Thus, *P. appendiculatum* is closely related chemically to *Marchantia polymorpha* and *M. paleacea* var. *diptera* (624, 794, 861).

Asterella, *Reboulia*, *Mannia*, and *Plagiochasma* species are related chemically since all give rise to macrocyclic bis-bibenzyls and hopane-type triterpenoids. The occurrence of the marchantin- and riccardin-type bis-bibenzyls in these species and in some *Marchantia* species (see Sect. 8.2.4.4) suggests that the Aytoniaceae have close affinities to the Marchantiaceae.

8.2.4.2 Conocephalaceae

The genus *Conocephalum* is the only member of family Conocephalaceae within the order Marchantiales. This genus has worldwide distribution. On the basis of morphological evidence, three *Conocephalum* species are known. *Conocephalum conicum* has long been regarded as morphologically and taxonomically homogeneous. Molecular studies have shown that this liverwort is a complex of five cryptic species (631). Analysis of the flavonoid composition of the European and American

species (518) and volatile components of the Japanese species (880) showed also differences within *C. conicum*. Recently, one of the cryptic species was described as separate species and named *Conocephalum salebrosum* (796). Within the genus *Conocephalum*, one more species is known. This is *C. japonicum*, which is morphologically different from the two above-mentioned species.

C. japonicum is not only morphologically distinct, but also chemically different from the other *Conocephalum* species. The major component of this liverwort is isolepidozene (307), the diastereomer of the widespread sesquiterpene hydrocarbon, bicyclogermacrene (293). Bicyclogermacrene (293), bicyclogermacren-14-al (295), and the germacrane alcohols 1(10),5-germacradiene-11-ol (698) and 1(10),5-germacradiene-4 β -ol (702), as well as germacrane- and the eudesmane-type sesquiterpene lactones, costunolide (709), dihydrocostunolide (711), and β -cyclocostunolide (656), have been detected as minor components (85, 492, 493). The presence of germacrane-type sesquiterpene lactones distinguishes this species from *C. conicum* and makes it rather similar to *Wiesnerella denudata* since *C. conicum* does not produce such compounds, while *W. denudata* elaborates the same lactones as those found in *C. japonicum* (45).

Conocephalum conicum produces monoterpenoids as the main components. Sabinene (44), which is the most common, in addition to β -myrcene (1), limonene (19), neryl acetate (11), camphene (55), and β -pinene (48), have been detected (492, 493). (+)-Bornyl acetate (58) and its derivatives (59–62) are the main components of the Japanese *C. conicum* grown in costal locations in comparison to two other chemotypes of *C. conicum* collected in Tokushima prefecture in Japan, which produce (–)-sabinene (44) and (*E*)-methyl cinnamate (1836) as the major volatile constituents (880). (*E*)-Methyl cinnamate (1836) is the characteristic compound of some populations of *C. conicum* growing in the USA (945). Recent investigations concerning volatile components from the cryptic species within the *C. conicum* complex have pointed out that this compound is a good chemical marker of cryptic species A, and is characteristic for the U.S. specimens (493). The *C. conicum* species growing in Europe (Italy, Greece, Romania, Spain) are very different chemically from the Japanese and American taxa, since the European species biosynthesize the brasilane-type sesquiterpene alcohol, conocephalenol (345) (40, 493). The same alcohol was also isolated from a German sample and its absolute configuration was established as 1*R*,9*S* (845).

Two populations investigated of the Japanese *C. conicum*, which belongs to cryptic species F, proved to be very distinct chemically from other samples investigated. Both of these produced mainly sesquiterpenoids, with the content of monoterpenoids being relatively low (493). The first species produced a large amount of germacrene D (692) while the second biosynthesized aromadendrane sesquiterpenoids, and, among these, cyclocolorenone (126) was the main component. Compound 126 is characteristic of leafy liverworts, especially *Frullania* and *Porella* species (45).

The chemical composition of *C. salebrosum* is very similar to that of *C. conicum*. This species is known as cryptic species S within the *C. conicum* complex.

C. salebrosum produces a relatively high amount of the sesquiterpene alcohol, cubebol (**462**), which seems to be good chemical marker of this species (**493**).

8.2.4.3 Wiesnerellaceae

There are three different chemical races of *Wiesnerella denudata*, the costunolide-guaianolide-type (I), the costunolide-type (II), and the guaianolide-type (III) (**893**). The guaianolides, zaluzanin C (**740**), zaluzanin D (**741**), and 8 α -acetoxyzaluzanin D (**743**), along with large amounts of neryl acetate (**11**), have been detected in the Japanese *W. denudata* (**492**). The Japanese *W. denudata* from a different collection was found to produce costunolide (**709**) and tulipinolide (**712**), but no guaianolides were detected (**893**). These results indicated that there are two chemotypes of *W. denudata* in Japan (types II and III).

The main constituent of *W. denudata* collected in Borneo is bornyl acetate (**58**), together with the other monoterpenoids, **19** and **57** (**490**). The above-mentioned monoterpenoids are responsible for the unique fragrant odor of this liverwort, which is almost identical to that of *Conocephalum conicum*, belonging to the bornyl acetate chemotype (**880**). Besides monoterpenoids, the Borneo specimen elaborated germacrane- and guaiane-type sesquiterpenoids. Costunolide (**709**), tulipinolide (**712**), dihydrotulipinolide (**713**), and 8 α -acetoxyzaluzanin D (**743**) have been detected in an ether extract of this liverwort (**490**). This Malaysian species belongs to the first chemotype of *W. denudata* (type I).

The East Malaysian specimen of the liverwort *W. denudata* elaborated not only germacranolides and guaianolides but also cyclic bis-bibenzyls. Marchantins A (**1577**) and B (**1578**) have been detected (**67**). It is noteworthy that bis-bibenzyls have not been found in the Conocephalaceae family to date (**45**).

The presence of tulipinolide and guaianolides in *W. denudata* indicates that this liverwort is more evolved chemically than *C. japonicum* since the latter species produces neither C-8 acetoxylated costunolide nor guaianolides, and is more advanced than *C. conicum*, because of the presence of germacrane-type sesquiterpene lactones (**45**).

According to a new classification of the Marchantiophyta, as presented in Table 1.1 (see page 5), *W. denudata* was separated from the Conocephalaceae and placed into the independent Wiesnerellaceae family. The chemical differences between *Conocephalum* spp. and *W. denudata* support this classification.

8.2.4.4 Marchantiaceae

The Marchantiaceae family comprises three genera, *Bucegia*, *Marchantia*, and *Preissia*. The monotypic genus *Bucegia* (*B. romanica*) elaborates solely a range of 8-hydroxyapigenin and 8-hydroxyluteolin glucuronides with variable levels of methylation and additional glycosylation (**511**). The only other species in this

family known to produce 8-hydroxyflavones at all is *Marchantia berteriana* (513). *M. berteriana* represents a conjunction between *Bucegia* and *Marchantia* species.

The New Zealand *M. berteriana* produces mainly cuparane sesquiterpenoids, among which cuparene (464) and 2-cuparenol (483) are the main components (72). Cuparanes, especially cyclopropanecuparenol (505), together with thujopsanes and chamigranes, are the main volatile components detected in *M. polymorpha*. There is no similarity in the chemical composition of the volatile components between *M. polymorpha* and two other species, *M. tosona* and *M. paleacea* var. *diptera*. β -Caryophyllene (426) and long-chain butenolides are characteristic for *M. paleacea* var. *diptera*, while isolepidozene (307) and β -barbatene (235) are the major components of *M. tosona* (492).

The most significant chemical markers of the Marchantiaceae family are the marchantin-type macrocyclic bis-bibenzyls (40, 45). The Japanese and German *M. polymorpha* produce marchantin A (1577) as the major component. This compound has not been detected in South African samples of this species, where its place as the major cyclic bis-bibenzyl was found to be taken by marchantin H (1583) (64). Marchantin E (1581) has been isolated from Indian and French specimens of this liverwort (40). It is obvious that the distribution of the marchantin-type bis-bibenzyls in *M. polymorpha* is geographically differentiated, although the morphology of this species collected in different countries is the same (488). The major component of the Ecuadorian *M. plicata* is marchantin A (1577) (571), while marchantin C (1579) has been detected as the main compound in the New Zealand *M. foliacea* (72). *M. paleacea* var. *diptera* and *M. palmata* also produce marchantin-type bis-bibenzyls. Marchantins A-C (1577–1579), marchantin E (1581), and isomarchantin C (1592) have been isolated from *M. paleacea* var. *diptera* (436, 794), while *M. palmata* elaborates marchantin C (1579), marchantin G (1582), and isomarchantin C (1592) (63). Two macrocyclic bis-bibenzyls, marchantin P (1591) and riccardin G (1569), have been isolated from *M. chenopoda* collected in Venezuela (840). Riccardin G (1569) belongs to the riccardin-type bis-bibenzyls, which are also widespread in *Marchantia* species. Besides *M. chenopoda*, this type of compound is biosynthesized by *M. palmata*, *M. polymorpha*, and *M. tosona* (40). It is worthy of mention that *M. polymorpha* also biosynthesizes perrottetin E (1638) and polymorphatin A (1576), which represents a new type of bis-bibenzyl skeleton (210). Perrottetin-type bis-bibenzyls are very rare in the Marchantiopsida class of the liverworts, and up to now have been only detected in *Asterella angusta* and *Monoclea forsteri* (635, 666).

Some of the *Marchantia* species produce their own particular compounds, which could be good chemical markers of these species. Thus, *M. chenopoda* was found to contain the new chenopodane-type sesquiterpenoids, chenopodene (917) and chenopodanol (918) (840, 849). (–)-1(10),11-Eremophiladien-9 β -ol (563) is a characteristic compound found in *M. polymorpha* subsp. *aquatica* (680), while long-chain butenolides (1948, 1949) seem to be good chemical markers of *M. paleacea* var. *diptera* (877).

The genus *Preissia* comprises a single species, *P. quadrata*, morphologically closely related to *Marchantia*. Campbell and associates (147), on the basis of

flavonoid chemistry, suggested that *P. quadrata* is closely related to *Conocephalum*. Analysis of the volatile components of the German collection led to the identification of germacrene C (**691**) and (+)-cubebol (**462**) as the main components. On the other hand, (–)-isolepidozene (**307**) and (+)-cubebol (**462**) were the main constituents of the same specimen collected in Austria (**433**). Cubebol (**462**) has been detected as the major component of *C. salebrosum*, while isolepidozene (**307**) is the most abundant compound occurring in *C. japonicum* and was also identified in *C. conicum* and *M. tosana* (**492**). The reinvestigation of the German *P. quadrata* by Asakawa's group (**74**) resulted in the isolation of riccardin B (**1565**) and neomarchantin A (**1595**), together with several common sesquiterpenoids such as barbatanes, bicyclogermacranes, caryophylanes, copaanes, cuparanes, elemanes, and germacranes. Despite the fact that the composition of the volatile components of *P. quadrata* is similar to those of *Conocephalum* species, the presence of marchantin- and riccardin-type bis-bibenzyls means that this liverwort is more closely related to *Marchantia* species, since the genus *Conocephalum* does not biosynthesize any bis-bibenzyls, as mentioned earlier.

8.2.4.5 Dumortieraceae

Dumortiera hirsuta is a large thallose liverwort that grows in humid sites, often close to water. Analysis of the Japanese *D. hirsuta* has revealed that there are three chemotypes for this liverwort: type I, which produces (4*S*,7*R*)-germacra-(1(10)*E*,5*E*)-dien-11-ol (**698**) and γ -cadinene (**346**); type II, producing mainly β -elemene (**283**) and elemol (**287**), and type III, with 3,4-dehydronerolidol as the main component (**45**, **883**). There are also a few geographical races of *Dumortiera hirsuta*. The Argentinean *D. hirsuta* elaborates three dumortane sesquiterpenoids (**553**–**556**), a rearranged dumortane (**557**), and a nordumortane (**558**), along with marchantin C (**1579**) (**96**, **876**). The Ecuadorian *D. hirsuta* accumulates the unusual α -pyrone derivatives, dumortins A–C (**1845**–**1847**) (**445**). *D. hirsuta* originated from mainland China and Borneo and produces dumhirone A (**1475**), a rare prenylethyl cyclohexadienone (**490**, **966**). The Japanese and Argentinean species do not elaborate such aromatic compounds.

It is known that *D. hirsuta* also produces cyclic bis-bibenzyls. Besides marchantin C (**1579**) detected in this liverwort collected in Argentina, this compound, together with isomarchantin C (**1592**) and riccardin C (**1566**), was isolated from a Japanese collection (**883**). Owing to the presence of the marchantin and riccardin bis-bibenzyls, *D. hirsuta* is allied chemically to *Marchantia* species, but, on the other hand, the presence of such compounds as dumortane sesquiterpenoids, α -pyrone derivatives, and/or prenylethyl cyclohexadienones, makes this species different from liverworts belonging to the family Marchantiaceae. In the new classification of the liverworts, *D. hirsuta* has been separated from the family Marchantiaceae and placed in the independent family Dumortieraceae.

8.2.4.6 Monoseleniaceae

The genus *Monoselenium* is the only member of the family Monoseleniaceae within the order Marchantiales, and only one species is known, *M. tenerum*.

From German and Chinese collections of *M. tenerum*, only two constituents have been detected using GC-MS. Analysis of the spectroscopic data of these two compounds suggested that the first is a new bibenzyl derivative, 3,5,4'-trimethoxybibenzyl (**1503**), and the second a phthalide, identified as 3-(4'-methoxybenzyl)-5,7-dimethoxyphthalide (**1807**) (488, 491, 492). The latter compound was isolated previously from the leafy liverwort *Frullania falciloba* (61, 502), belonging to the order Porellales in the class Jungermanniopsida. Bibenzyls are widespread among leafy liverworts, especially in *Frullania* and *Radula* species, and only a few such compounds have been detected from the thallose liverworts.

The chemical composition of *M. tenerum* is different from that of all Marchantiales species so far investigated. It is interesting to note that the present species is closely related chemically to the *Frullania* (Jungermanniopsida) chemotype II, producing bibenzyls as the major products (see Sect. 5.3.6.4).

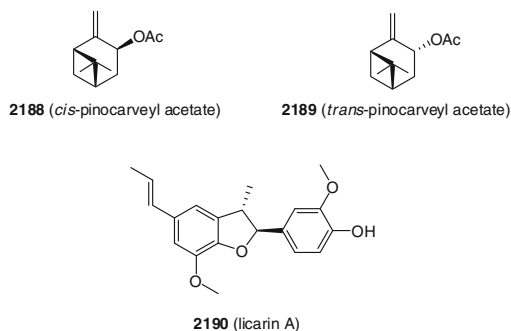
8.2.4.7 Monocleaceae

The Monocleaceae is a family of the liverworts with only one genus, *Monoclea*, containing two species, *M. forsteri* and *M. gottschei*. They are distributed only in New Zealand and South and Central America. It is suggested that *Monoclea* is taxonomically very old and Gondwana-derived (146, 266). The previous classifications of the Marchantiophyta recognized a separate order, Monocleales, but later molecular studies show that *Monoclea* is closely related to the genus *Dumortiera*. In the new classification of the liverworts, Monocleales has been incorporated into the Marchantiales (168).

Monoclea ferskii produces marchantin-, perrottetin-, and riccardin-type bis-bibenzyls together with unsaturated fatty acids with an ene-yne system (40). Chemical analysis of this species has shown also the presence of sesquiterpenoids (72), but the content of these compounds is considerably lower than in *M. gottschei* (771). Like *M. forsteri*, the latter species also produces bis-bibenzyls. Marchantin C (1579), neomarchantin A (1595), and perrottetin E (1638) have been detected (266). However, neither riccardin-type bis-bibenzyls nor fatty acids with an ene-yne partial structure has been isolated from *M. gottschei*. In terms of their flavonoid profiles, *M. gottschei* populations have shown to accumulate a much more diverse range of structural flavonoid types than *M. forsteri* (510). *M. gottschei* produces mainly 6-oxygenated flavones and di- and triglycosylate flavones (40, 266). *M. forsteri* was shown to attach "polysaccharides" (di- or trisaccharides) to the flavone aglycone (1905–1908) (510). The structures of these di- or trisaccharides bear a striking resemblance to the glycosidic moieties of several *M. gottschei* flavone glycosides (510). The occurrence of marchantin bis-bibenzyls and glucuronide and galacturonide flavone glucosides in the genus *Monoclea* supports the placement of the family Monocleaceae in the order Marchantiales.

8.2.4.8 Targioniaceae

Targionia species are very small thalloid liverworts. The French *T. hypophylla* emits an intense fragrant odor when crushed. The chemical analysis of this species led to the isolation of *cis*- (**2188**) and *trans*-pinocarveyl acetates (**2189**), which showed a characteristic aroma (60). The occurrence of monoterpenoids among liverworts belonging to the Marchantiales is characteristic for *Conocephalum*, *Wiesnerella*, and *Asterella* species. The Portuguese *T. lorbeeriana* also produces an essential oil (621), but the most characteristic compounds of this liverwort are sesquiterpene lactones (620). This species elaborates the germacranolides **705** and **706** and guaianolides **744–746**, of which dehydrocostus lactone (744) is the predominant component (620). Thus, *T. lorbeeriana* is very closely related chemically to *Wiesnerella denudata* (Wiesnerellaceae) (see Sect. 8.2.4.3), because both liverworts produce the same germacranolide and guaianolide series, although they are morphologically quite different. The presence of monoterpenoids and the absence of bis-bibenzyls shows that the Targioniaceae family is also similar to the Conocephalaceae (see Sect. 8.2.4.2).



cis- and *trans*-Pinocarveols found in *Targionia hypophylla* and licarin A from *Jackiella javanica*

8.2.4.9 Ricciaceae

The Ricciaceae comprise two genera, *Ricciocarpos* and *Riccia*. *Riccia* species constitute one of the most distinct genera within the Marchantiales. The chemical composition of the species analyzed is quite different from those of other thallose liverworts. *Riccia* species produce lunularin (**1477**), lunularic acid (**1478**), phytosterol mixtures, and a wide range of saturated, monoenoic and polyenoic fatty acids, including acetylenic forms (39, 40, 190, 419). The occurrence of acetylenic fatty acids is very characteristic of *Riccia* species. These compounds are very rare among the Marchantiophyta, and up to now have been detected only in two other species, *Monoclea forsteri* and *Pellia neesiana* (190, 419). Chemical analysis of flavonoid constituents in the family Ricciaceae has revealed that *Riccia* species produce a wide range of apigenin and luteolin glucuronides (512, 519). *R. fluitans* shows a remarkable ability to modify luteolin glycosides including ferulylation and

hydroxypropionylation of glucose or glucuronic acid. Acylated apigenin 7-*O*-glucuronides have been also detected in *R. crystallina* (519).

The chemical constituents of a Japanese specimen of *Ricciocarpos natans* from a field collection were found to be quite different from those of *in vitro*-cultured European species. Lunularic acid (1478), stigmasterol (1421), sitosterol (1426), and the steroid ketones 1424 and 1428 have been isolated from the former species. GC/MS analysis showed the presence of polyenoic fatty acids (974). It is worth mentioning that in comparison to *Riccia* species this liverwort was free of acetylenic fatty acids (419). An auxenic-cultured specimen produced cuparane and monocyclofarnesane sesquiterpenoids, bibenzyls, lunularin (1477), and lunularic acid (1478), the phenylpropanoid glycosides 1862 and 1863, bibenzyl glycosides, and also the riccardin-type cyclic bis-bibenzyl, riccardin C (1566), and its dimer, pusilatin B (1653) (452, 453, 964). The presence of compounds 1862 and 1863, cuparanes, and riccardin-type bis-bibenzyls make this liverwort chemically similar to *Marchantia polymorpha* (40, 634). *M. polymorpha* is also the second liverwort to produce bibenzyl glycosides (667). An analysis of flavonoids occurring in *R. natans* (512) showed that this liverwort elaborates luteolin and apigenin mono- and diglycosides. In each case, the sugar was identified as glucuronic acid, which is very characteristic for all liverworts belonging to the order Marchantiales. There are no chemical affinities between *Riccia* and *Ricciocarpos* species.

8.2.4.10 Corsiniaceae

The genus *Corsinia* is the only member of the Corsiniaceae family. Chemical investigations have shown that Spanish and Turkish specimens of *Corsinia coriandrina* produce corsifurans A-C (1815–1817), which possess the 2-(4-methoxyphenyl)-benzofuran skeleton (79, 920). This liverwort also produces stilbenoids, *e.g.* (*E*)-(1485) and (*Z*)-3,4'-dimethoxystilbene (1486) (79). Since a stilbenoid origin of corsifurans has been suggested, the co-occurrence of both groups of compounds is apparent from a biogenetic point of view (920). Interestingly, the co-occurrence of the structurally related isothiocyanates and *S,S*-dimethyl iminodithiocarbonates in *C. coriandrina* has been found. The coriandrins, 1882 and 1883, and the *O*-methyltridentatols, 1884 and 1885, have been isolated from the essential oil of *C. coriandrina* collected in Spain (921). Their presence in this liverwort as naturally occurring constituents has been confirmed by independent detection of these compounds in a Turkish sample (79).

The chemical composition of *C. coriandrina* is quite different from that of all Marchantiales species so far investigated chemically. Coriandrins and *O*-methyltridentatols have been detected only from this one species. 2-Arylbzenzofurans, structurally similar to corsifurans, but of neolignan origin, namely, licarin A (2190) and egonol 2-methylbutanoate (1861), have been found in *Jackiella javanica* (order Jungermanniales) (40) and *Riccardia multifida* subsp. *decrescens* (order Metzgeriales) (972).

8.2.4.11 Cyathodiaceae

The genus *Cyathodium* is distributed worldwide with eleven validly recognized species (783), but only one species has been investigated chemically thus far (494). *C. foetidissimum* is characterized by its very intense unpleasant odor. GC/MS analysis of an ether extract showed the presence of skatole (1878), which is a well-known compound produced by biodegradation of tryptophan that is responsible for the fecal odor of this liverwort (494). This is the second record of skatole (1878) in the Marchantiophyta. Previously, this compound was detected in an *Asterella*-like liverwort collected in Malaysia (71). *Cyathodium foetidissimum* also elaborates isolepidozene (307) and lunularin (1477). Isolepidozene (307) is known as the main volatile component of *Conocephalum japonicum* and *Marchantia tosona* (492). Lunularin (1477) was previously isolated from or detected in *Dumortiera hirsuta*, *Marchantia polymorpha*, *M. chenopoda*, *M. berteriana*, *M. paleacea* var. *diptera*, and *Ricciocarpos natans* (40). All these species are thallose liverworts and belong to the order Marchantiales of the Marchantiophyta. *C. foetidissimum* is closely related chemically to the Marchantiopsida.

8.3 Chemosystematics of Jungermanniopsida

8.3.1 Order Pelliales

8.3.1.1 Pelliaceae

The Pelliaceae is a family of liverworts with only two genera: *Pellia* and *Noteroclada*. The two genera are morphologically very different, because *Noteroclada* has a leafy appearance, while *Pellia* is more clearly thallose.

The genus *Pellia* is a small liverwort widespread in temperate areas of the Northern Hemisphere. Up to the present, three species, *P. endiviifolia*, *P. epiphylla*, and *P. neesiana*, have been analyzed chemically. *Pellia* species are quite characteristic in this regard since they produce sacculatane-type diterpenoids (45). The most typical compounds of *P. endiviifolia* are sacculatal (1348), which possesses a pungent taste, with the non-pungent C-9 isomer, isosacculatal (1349) and the related compounds 1350, 1351, 1357, 1359, and 1363–1372 also evident (311, 312, 492). The bis-bibenzyls, perrottetin E (1638) and its 11'-methyl ether have also been detected (40). *P. neesiana* also elaborates sacculatal (1348), the same perrottetin-type bis-bibenzyls (45), and a wide range of saturated, monoenoic and polyenoic fatty acids including acetylenic forms (190).

Pellia epiphylla is similar to *P. endiviifolia* and *P. neesiana* since it contains sacculatane diterpenoids and bis-bibenzyls (175, 176, 492). However, the chemical constituents of the former liverwort are more complex than the latter two species. Besides the two above-mentioned classes of compounds, *P. epiphylla* produces

various types of sesquiterpenoids, and also bibenzyls, lignans, sterols, flavonoids, and fatty acids. It is noteworthy that the africane-type sesquiterpenoids, **87**, **89–91**, and **99**, which are rare in Nature, have been isolated from gametophytes and sporophytes of this species ([175](#), [176](#)). Africane sesquiterpenoids are characteristic for *Porella* species belonging to the Porellaceae (see Sect. [8.3.6.1](#)), especially for *P. swartziana* ([126](#), [848](#)). Other very rare natural products are bis-bibenzyl dimers, with *P. epiphylla* biosynthesizing 13',13'''-bis(10'-hydroxyperrottetin E) (**1657**) ([182](#)). Among the perrottetin-type bis-bibenzyl dimers, only one other compound is known, cruciatin (**1659a**) (the perrottetin F dimer), from *Lunularia cruciata* (Lunulariaceae) ([40](#)).

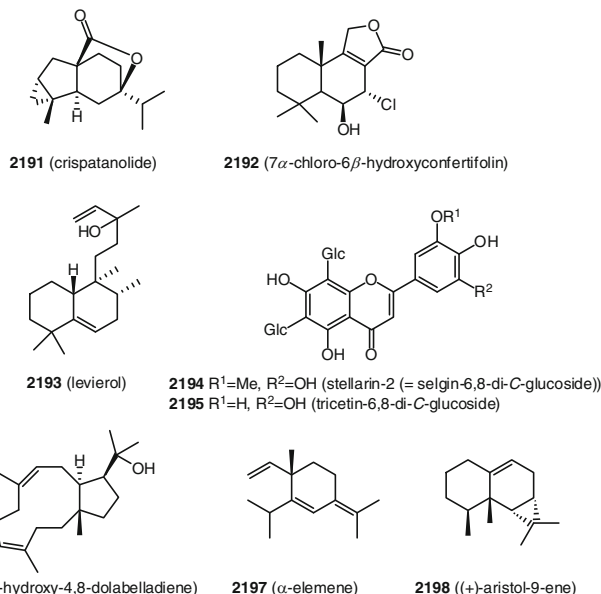
The *Noteroclada* species are not only morphologically distinct but also chemically different from the *Pellia* genus. The Ecuadorian *N. confluens* produces mainly bicyclogermacrene (**293**), brasila-5(10),6-diene (**342**), brasila-1,10-diene (**344**), dactylol (**938**), α -isocomene (**939**), sativene (**791**), pacifigorgia-1,10-diene (**836**), and pacifigorgia-1(6),10-diene (**837**) ([492](#)). It is noteworthy that brasilanes have been detected in *Conocephalum conicum* belonging to the Conocephalaceae (Marchantiales) ([543](#)), while pacifigorgiane-type sesquiterpenoids are characteristic for *Frullania tamarisci* (Frullaniaceae, Porellales) ([644](#)).

8.3.2 Order Fossombroniales

8.3.2.1 Makinoaceae

Makinoa crispata is the only species in the genus *Makinoa*. On the basis of chemical analysis, three chemotypes of *M. crispata* have been proposed. Type I biosynthesizes the characteristic eudesmanolide, crispatanolide (**2191**) ([40](#), [45](#)). Type II produces dactylol (**938**) and bicyclogermacrene (**293**) as major compounds ([492](#), [726](#)). Type III elaborates makinin (**1417**), an *abeo*-abietane diterpenoid ([474](#)). It is noteworthy that types I and II have been found in Japanese specimens, and, besides the compounds mentioned, both types also produce the non-pungent sacculatane-type diterpene dialdehyde, perrottetianal A (**1354**), together with the drimane sesquiterpenoid, cinnamolide (**546**), and the characteristic chlorine-containing drimane, 7 α -chloro-6 β -hydroxyconfertifolin (**2192**) ([40](#), [304](#), [492](#)). The third chemotype occurring in Taiwan is isolated from the former two Japanese chemotypes, since it does not contain either the sesquiterpenoids mentioned above or the sacculatane diterpenoids. Besides makinin (**1417**), the Taiwanese population produces fatty acids and their methyl and ethyl esters ([474](#)).

The presence of perrottetianal A (**1354**) and dactylol (**938**) makes *M. crispata* chemically very similar to *Pellia* and *Noteroclada* species, respectively (see Sect. [8.3.1.1](#)). On the other hand, drimane-type sesquiterpenoids are widespread in foliose *Porella* species (see Sect. [8.3.6.1](#)). Since simple thalloid and leafy liverworts have been united morphologically and chemically in the Jungermanniopsida class of the Marchantiophyta, *M. crispata* exemplifies the close relationship between both morphologically different classes of liverworts.



Crispatanolide and 7 α -chloro-6 β -hydroxyconfertifolin found in *Makinoa crispata*, levierol in *Pallavicinia levieri*, and stellarin-2, tricitin 6,8-di-*C*-glucoside, 18-hydroxy-4,8-dolabelladiene, α -elemene and (+)-aristol-9-ene in Pleuroziaceae species

8.3.2.2 Fossombroniaceae

The Fossombroniaceae family comprises two genera, *Fossombronia* and *Austrofossombronia*. All species therein are small and thallose, with the thallus typically ruffled to give the appearance of being leafy.

Fossombronia angulosa collected in Greece produced acetogenins previously reported in brown algae (383) as the main components. Dictyotene (1936), (*Z*)-multifidene (1938), and dictyoptere (1939) have been detected (492). Recently, dictyotene (1936) and (*E*)-ectocarpene (1937) have also been detected in *Chandonanthus hirtellus* collected in Tahiti (494). These results suggest that some liverworts originate from algae (40). The marine algal components in *Fossombronia* species are extremely interesting since the species is similar morphologically to some marine algae, for example, *Ulva* species. *Chandonanthus* is a leafy liverwort belonging to the family Scapaniaceae, but phylogenetically both species are placed in the Jungermanniopsida class of liverworts.

Besides acetogenins, *F. angulosa* also biosynthesizes the cythane-type diterpenoids, 2 β ,9 α -dihydroxyverrucosane (1055) and 5,18-dihydroxy-*epi*-homoverrucosane (1071) (492). Compound 1071, together with a wide range of neoverrucosanes (1056, 1062, 1063, 1065–1067), has been isolated from axenic cultures of the Arctic liverwort *F. alaskana* (269). This liverwort also produces the hopane-type triterpenoids 1436, 1439–1442, and tetrahymanol (1447), belonging to the gammacerane series (268). Tetrahymanol (1447) together with the hopanes, has

been found also in *F. pusilla* (268). Phylogenetically, tetrahymanol and the hopanoids found in spore-forming plants, lichens, and fungi are closely related. They can be considered as primitive triterpenoids, since they are devoid of an oxygenated function at C-3, in contrast to the triterpenes of all higher plants (125, 415, 684). Besides triterpenoids, *F. pusilla* also produces the sacculatane diterpenoids **1354** and **1355** (40). A range of sacculatane-type diterpenoids has been found also in the *in vitro*-cultured *F. wondraczeki* (216). As previously mentioned, sacculatanes are characteristic compounds occurring in *Pellia* species, and have been detected additionally in *Makinoa crispata* belonging to the same order, Fossombroniales.

8.3.3 Order Pallaviciniales

8.3.3.1 Hymenophytaceae

The Hymenophytaceae is a taxonomically distinct family with *Hymenophyton* as the sole genus. Two *Hymenophyton* species have been described, namely, *H. flabellatum* and *H. leptopodium* (658). Both these species are morphologically and chemically similar. Analysis of their flavonoids resulted in the detection of apigenin 6,8-di-*C*-pentosides and pentoside-hexosides in both taxa. However, *H. leptopodium* produces additionally kaempferol *O*-glycosides, which are absent in *H. flabellatum* (517). The flavone *C*-glycosides and flavonol *O*-glycosides are characterized by significant biosynthetic differences. Owing to this fact, on the basis of their flavonoid patterns, both *Hymenophyton* species are distinguishable, even contrary to their morphological similarities (517).

The New Zealand *H. flabellatum* elaborates the phenyl butenone, 1-(2,4,6-trimethoxy-phenyl)-but-(2*E*)-en-1-one (**1852**), and the related compounds **1853–1857** (77, 900). The 4-chromanones, **1849–1851**, have also been isolated from this liverwort (900). *H. flabellatum* is one of the most chemically isolated liverworts so far examined, because no phenyl butanones have been detected in any other liverwort. It is worth mentioning that compounds **1851** and **1852** have been found in the Japanese fern, *Arachinoides standishii* (803). Such a chemical similarity suggests that some liverworts and ferns are also closely related phylogenetically.

8.3.3.2 Pallaviciniaceae

The Pallaviciniaceae is a widely distributed family of the liverworts, which contains seven genera, among which *Pallavicinia* and *Symphyogyna* are the most widespread. *Pallavicinia* species are simple thalloid liverworts. Chemical analysis of several *Pallavicinia* species has afforded a number of common sesquiterpenoids, sterols, and carbohydrates (39, 40, 882). Interestingly, the Japanese- and Taiwanese-derived *P. subciliata* produces rearranged 7,8-*seco*-labdane-type diterpenoids.

Pallavicinin (**1295**) and neopallavicinin (**1297**) have been isolated from both collections (475, 887, 954). The Japanese specimen additionally elaborates other *seco*-labdanoids (**1296**, **1298–1307**) and the two clerodane alcohols **967** and **970** (702, 887). Analysis of *P. subciliata* collected from different localities suggests that, on the basis of their chemical composition, three chemotypes of this liverwort can be recognized. Chemotype I biosynthesizes the rearranged 7,8-*seco*-labdanoids, chemotype II produces mainly a clerodane alcohol, kolavelool (**967**) with no labdanes detected, while chemotype III elaborates both labdane- and clerodane-type diterpenoids (475).

The Chinese *P. ambigua* is closely related chemically to *P. subciliata*. Compounds **1295**, **1296**, and **1297** have been found in this species (468). On the other hand, *P. levieri* is chemically distinct from the two *Pallavicinia* species mentioned above, since this liverwort produces the pungent dialdehyde, sacculatal (**1348**), together with the chattaphanin-type diterpenoid (rearranged labdane), levierol (**2193**) (40). An isomer of sacculatal, perrottetianal A (**1354**), has been isolated from *Symphyogyna brongniartii* (40). Thus, *P. levieri* is chemically more similar to species in the genus *Symphyogyna*, which is also classified in the Pallaviciniaceae family.

The Venezuelan *Symphyogyna brasiliensis* produces a diterpenoid named symphyogynolide (**1289**) (843), which is of the same type of rearranged labdane lactone as pallavicinin (**1295**) found in *Pallavicinia subciliata* and *P. ambrigua* (468, 887). However, compound **1289** has not been detected in the Ecuadorian *S. brasiliensis*. This liverwort produces dihydro- β -agarofuran (**941**) as the main component (492). Compound **941** is a sesquiterpenoid based on the tricyclic 5,11-epoxy-5 β ,10 α -eudesmane skeleton. Besides **941**, other eudesmanes have been detected, namely, δ -selinene (**578**), selina-4,7-diene (**581**), cascarilladiene (**596**), and eudesma-5,7(11)-diene (**597**) (492).

In the new classification of the liverworts, *Symphyogyna* was separated from the Hymenophytaceae and placed in the family Pallaviciniaceae (168, 169). Chemical evidence supports this classification, since there is no chemical affinity between *Hymenophyton* and *Symphyogyna* (45).

Liu and Wu studied the chemical constituents of *Jensenia spinosa* (= *Pallavicinia stephanii*) and found that it produces pallavicinin (**1295**) as the major component (475). Thus, the genera *Pallavicinia*, *Symphyogyna*, and *Jensenia* are closely related chemically. The above data indicate that diterpenoids of the labdane-, clerodane-, and sacculatane-types are the three main classes of compounds biosynthesized by liverworts belonging to the family Pallaviciniaceae.

8.3.4 Order Pleuroziales

8.3.4.1 Pleuroziaceae

The Pleuroziaceae is a distinctive family among the Jungermanniopsida class of liverworts. This family was formerly classified in the order Jungermanniales, but

recent molecular results have pointed out that the genus *Pleurozia* is more closely related to simple thallose liverworts than to the leafy liverworts. In the new classification of the Marchantiophyta, this family was placed into the independent order Pleuroziales, within the subclass Metzgeriidae (see Table 1.1) (168, 169). The Pleuroziaceae comprises two genera, named *Pleurozia* and *Eopleurozia*.

The analysis of the flavonoids occurring in liverworts belonging to the Pleuroziaceae showed that both genera, *Pleurozia* and *Eopleurozia* produce the same “marker flavonoids”: lucenin-2 (1903), stellarin-2 (2194), and tricetin 6,8-di-*C*-glucoside (2195) (557). All flavonoids mentioned above belong to the flavone-di-*C*-glycoside series. The largest variety of compounds of different structural types has been detected in *Eopleurozia* species. These results support the phylogenetically more primitive position of *Eopleurozia* compared to *Pleurozia*. Mues and associates recognized three *Pleurozia* chemotypes (557). Type 1, including *P. acinosa*, *P. caledonica*, and *P. articulata*, apart from “marker flavonoids”, produces 3'-*O*-glucosylated lucenin-2. *P. conchifolia*, classified in type 2, elaborates the “marker flavonoids” and two further luteolin-*C*-glycosides. The third group, comprising *P. gigantea*, *P. purpurea*, *P. giganteoides*, and *P. heterophylla*, is characterized by the presence of only the “marker flavonoids”. Due to their reduced flavonoid pattern, the species belonging to the third chemotype are regarded as the most advanced in the family.

Analysis of terpenoid constituents of the two *Pleurozia* species, *P. acinosa* and *P. gigantea*, demonstrated that both species are similar chemically, since both produce the same clerodane-type diterpenoid, kolavelool (967) and the labdane-type diterpenoid, 8-*epi*-sclareol (1242) (65, 950). From the latter species, additionally fusicoccanes 1095, 1098, 1099, and 1102, 18-hydroxy-4,8-dolabelladiene (2196), and the chattaphanin-type diterpenoid, pleuroziol (1308), have been isolated (65, 488). In contrast to *P. gigantea*, *P. acinosa* produces the widespread liverwort sesquiterpene hydrocarbons, bicyclogermacrene (293), β -chamigrene (436), and α - (2197), β - (283), and δ -elemene (282). *P. acinosa* elaborates also (+)-aristol-9-ene (2198) (950). Based on terpenoid chemistry, it is suggested that *P. gigantea* is a more advanced species than *P. acinosa*. This sentiment is in agreement with the flavonoid chemistry of the Pleuroziaceae family.

8.3.5 Order Metzgeriales

8.3.5.1 Metzgeriaceae

The *Metzgeria* genus comprises small simple thalloid liverworts of more than 100 species altogether. The absence of oil bodies in *Metzgeria* species correlates with the absence of terpenoids in these liverworts. Among the species investigated, *M. furcata*, *M. rufula*, *M. temperata*, *M. albinea*, and *M. conjugata*, only in *M. furcata* have β -caryophyllene (426) and cuparene (464) been detected (72). Other *Metzgeria* species elaborate sterols and fatty acids (39, 40, 882). *M. rufula*

produces the unusual nitrogen-containing rufulamide (1887) (446). On the other hand, chemical investigation of phenolic metabolites has revealed that *Metzgeria* species are rich sources of flavonoids (555, 829). *M. leptoneura* synthesizes tricetin 6-*C*-xyloside-8-*C*-hexoside as the major component, whereas from *M. conjugata*, tricetin and apigenin di-*C*-glycosides have been isolated (829). On the basis on its flavonoid glycoside distribution, *M. furcata* var. *furcata* has been divided into three chemotypes, namely, type I: the tricetin-apigenin-type, type II: the apigenin-type, and type III: the apigenin-luteolin-type (555).

In comparison to *Metzgeria* species, *Apometzgeria pubescens* elaborates sesqui- and diterpenoids. Cuparanes 464, 483, 487, and 489, maalianes 795 and 800, together with β -barbatene (235), bicyclogermacrene (293), β -elemene (283), γ -cadinene (346), and *ent*-16-kaurene (1133), have been detected in a Japanese specimen (882). Like *Metzgeria* species, *A. pubescens* also produces sterols and fatty acids (882), and this liverwort is also a rich source of flavonoids. Eleven flavone di-*C*-glycosides (mainly tricetin *C*-glycosides and its methyl ethers) have been detected in a specimen of this liverwort originating from Switzerland (828).

8.3.5.2 Aneuraceae

Among the five genera classified within the Aneuraceae family only three have been chemically investigated, *Aneura*, *Cryptothallus*, and *Riccardia*. The composition of the terpenoid and aromatic compounds of *Aneura* and *Cryptothallus* is quite different from that of *Riccardia*. *A. pinguis* and *C. mirabilis* produce pinguisane-type sesquiterpenoids, which are also chemical markers of some leafy liverworts, such as *Porella*, *Lejeunea*, and *Ptilidium* species, but pinguisanes do not occur in *Riccardia* species (40, 688, 812).

Riccardia species (Fig. 8.2) produce various sesquiterpenoids and aromatic compounds as the major components. At present, 16 *Riccardia* species have been investigated chemically, and *R. andina*, *R. jackii*, *R. prehensilis*, *R. eriocaula*, *R. nagasakiensis*, *P. palmata*, and *R. miyakeana* produce sesquiterpenoids as the main components (39, 40, 72, 141, 882). Among the species mentioned, *R. eriocaula* is quite distinct chemically since it elaborates cuparane-type sesquiterpenoids. The main component of the volatile fraction is 2-cuparenol (483) together with cuparene (464) and 1,2-dihydroxy- α -cuparenone (486) (72). Elemene-type sesquiterpenoids are the most often reported compounds occurring in *Riccardia* species.

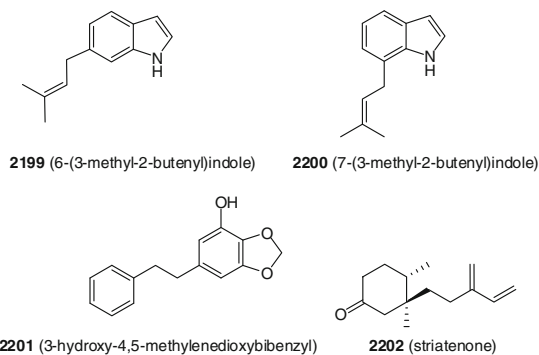
Japanese and New Zealand samples of *Riccardia crassa* have produced very characteristic sesquiterpene-quinols. Riccardiphenol A (924a) and B (924b) have been isolated from the Japanese specimen and riccardiphenol C (924) from the New Zealand collection (651, 859). These compounds have been detected only in *R. crassa*, so sesquiterpene-quinols seem to be good chemical markers for this species.

Riccardia incurvata, *R. chamedryfolia*, and *R. multifida* are chemically very similar because of the presence of prenyl indoles (2199, 2200) (39, 40, 56). *R. chamedryfolia* additionally produces 3-hydroxy-4,5-methylenedioxybibenzyl (2201) (39). Unique chlorinated bibenzyls are characteristic compounds for the



Fig. 8.2 *Riccardia* sp. (Permission for the use of this figure has been obtained from Prof. Dr. Rob Gradstein, Paris, France)

Chilean *R. polyclada* and New Zealand *R. marginata*. Compounds **1550–1552** have been isolated from *R. marginata*. These bibenzyls are characterized by a lack of substitution in the second benzene ring, in comparison with compounds **1553–1556**, isolated from *R. polyclada* (94, 458).



Prenyl indoles and a bibenzyl found in *Riccardia* species and striatenone from *Porella cordaeana* and *P. navicularis*

Riccardia multifida, *R. multifida* subsp. *decrescens*, and *R. nagasakiensis* are known for the biosynthesis of riccardin- and marchantin-type macrocyclic bis-bibenzyls. The former two taxa elaborate riccardins A (**1564**) and B (**1565**), together with marchantin I (**1584**) (583, 836, 972). The last-mentioned liverwort produces marchantin C (**1579**), instead of marchantin I (141). Interestingly, *R. multifida* subsp. *decrescens* produces the bis-bibenzyl dimer, pusilatin E (**1656**) (972). Pusilatin is a riccardin C dimer and have been also detected in *Blasia pusilla* and *Ricciocarpus natans* (see Sects. 8.2.1.1 and 8.2.4.9).

There is no chemical affinity between *R. lobata* var. *yakushimensis* and the other *Riccardia* species. This liverwort produces the characteristic pungent compound, sacculatol (1348), which is the major component of *Pellia endiviifolia*, and its C-9 epimer (1349) (58). This chemical similarity between *R. lobata* var. *yakushimensis* and *Pellia endiviifolia* is in agreement with morphological features, because the former liverwort is not only chemically but also morphologically similar to the latter species.

8.3.6 Order Porellales

8.3.6.1 Porellaceae

Porella is a large, common, and widespread genus of liverworts, which comprises more than 100 species. Twenty-nine *Porella* species have been investigated chemically and are known to produce many kinds of secondary metabolites, especially sesquiterpenoids. Pinguisanes, aromadendranes, germacrane, lepidozanes, guaianes, drimanes, santalanes, monocyclofarnesanes, africanes, and a minor group of sesquiterpenoids have been found in *Porella* species. On the basis of their chemical composition, *Porella* species have been divided into six types; the drimane- (I), sacculatane- (II), pinguisane-sacculatane- (III), guaiane-germacrane- (IV), pinguisane- (V), and african- (VI) types (Table 8.1) (495).

The biggest group is type I, which comprises the pungent liverworts, *P. arboris-vitae*, *P. canariensis*, *P. fauriei*, *P. gracillima*, *P. obtusata* var. *macroloba*, *P. roellii*, and *P. vernicosa* (*Porella vernicosa* complex). All of these liverworts produce the hot-tasting drimane-type sesquiterpenoid, polygodial (548) (39, 40, 179, 637, 821). Apart from polygodial (548), all of these species contain other drimanes, among which cinnamolide (546), drimeninol (543), and drimenin (545) are the most widespread (39, 40). The co-occurrence of the aromadendrane-type sesquiterpenoid, cyclocolorone (126) as well as pinguisane-type sesquiterpenoids with the drimanes has been detected in five of seven species belonging to type I. Up to the present time, in *P. fauriei* and *P. roellii* only drimane-type sesquiterpenoids have been found.

Liverworts belonging to type II accumulate characteristic sacculatane-type diterpenoids. *Porella camphyophylla*, *P. perrottetiana*, and *P. stephaniana* produce perrottetianal A (1354) as the main component (39, 40). Perrottetianal B (1355) and sacculaporellin (1373) have been detected additionally in *P. perrottetiana* (39, 40). This liverwort also elaborates labdane diterpenoids and (–)- α -eudesmol (600) (40, 892). Alcohol 600 is an abundant component and is thus a valuable chemical marker for *P. perrottetiana*.

There are a few *Porella* species that, besides sacculatane-type diterpenoids, produce remarkably large amounts of pinguisane-type sesquiterpenoids. These are *P. platyphylla*, *P. grandiloba*, *P. elegantula*, *P. japonica*, and *P. acutifolia* ssp. *tosana*. The former three species are included in the sacculatane-pinguisane-type (III). However, the latter two liverworts have been separated from this group, since besides the compounds mentioned they biosynthesize very

Table 8.1 Chemotypes of *Porella* species

Types	<i>Porella</i> species	Sesquiterpenoids										Diterpenoids			
		DRI*	PIN	ARO	GER	GUA	AFR	MON	SAN	ELE		SAC	LAB	KAU	
I	<i>Porella arboris-vitae</i>	++++	+	+											
	<i>Porella canariensis</i>	+	+	+											
	<i>Porella fauriei</i>	++													
	<i>Porella gracillima</i>	+++	+++	++											
	<i>Porella obtusata</i> subsp. <i>macroloba</i>	+++	+++	++											
	<i>Porella roellii</i>	+++	+++												
	<i>Porella vernicosa</i>	+++	+++	+											
II	<i>Porella camphylophylla</i>														
	<i>Porella perrottetiana</i>														
	<i>Porella stephaniana</i>														
	<i>Porella elegantula</i>														
III	<i>Porella grandiloba</i>														
	<i>Porella navicularis</i>														
	<i>Porella platyphylla</i>														
	<i>Porella acutifolia</i> subsp. <i>tosana</i>														
IV	<i>Porella japonica</i>														
	<i>Porella cordaeana</i>														
	<i>Porella densifolia</i>														
	<i>Porella recurva</i>														
V	<i>Porella caespitans</i> subsp. <i>setigera</i>														
	<i>Porella subobtusata</i>														
	<i>Porella swartziana</i>														
VI	<i>Porella caespitans</i> subsp. <i>setigera</i>														
	<i>Porella subobtusata</i>														
	<i>Porella swartziana</i>														

*DRI drimanes, PIN pinguianes, ARO aromadendranes, GER germacrane, GUA guaianes, AFR africanes, MON monocyclofarnesanes, SAN santalanes, ELE elemenes, LAB labdanes, SAC sacculatanes, KAU kauranes

characteristic guaiane- and germacrane-type sesquiterpene lactones (type IV) (39, 40, 315, 316). It is worth mentioning that both liverworts produce guaia-12,6-olides, but, in the case of their germacranolide constituents, *P. acutifolia* subsp. *tosana* biosynthesizes 12,8-olides, while *P. japonica* produces 12,6-olides (865). Reinvestigation of *P. acutifolia* subsp. *tosana* collected in Kochi, Japan resulted in the isolation of the *Diels-Alder* reaction-type pinguisane dimers, bisacutifolones A-C (854–856), which have not been isolated from any other *Porella* species. Pinguisanes, sacculatanes, and germacranolides have also been detected, but, however, the presence of guaianes and hydroperoxygermacranolides (715, 716) in this collection has not been confirmed (315, 322). This observation implies that there are two chemotypes of *P. acutifolia* subsp. *tosana* in Japan, with one pungent and the other not, since hydroperoxygermacranolides (715, 716) are responsible for the pungent taste of the liverwort growing in Tokushima (865).

Porella recurva, *P. cordaeana*, *P. navicularis*, as well as *P. densifolia* ssp. *appendiculata* and *P. densifolia* var. *fallax* (type V) produce pinguisanes as the main components. Pinguisane-type sesquiterpenoids are widespread in the genus *Porella*, but the species belonging to this group do not seem to produce many other sesquiterpenoids besides pinguisanes. From *P. recurva*, only the norpinguisanes 860, 861, 881, and 882 have been isolated (913). In *P. cordaeana* and *P. navicularis*, besides norpinguisanes, also pinguisanes have been found (40, 143). The monofarnesane-type sesquiterpenoid striatenone (2202) and drimanes have also been detected in *P. cordaeana* and *P. navicularis* (40). Compounds 808 and 809 have also been found in *P. densifolia* subsp. *appendiculata*, and *P. densifolia* var. *fallax* together with kaurane-type diterpenoids (62). Among all investigated *Porella* species, kauranes have been isolated only from these two species. Labdane- (1281), phytane- (1323), pimarane- (1331), and rosane-type (1336) diterpenoids have been detected in *P. navicularis* (143).

Porella species that biosynthesize african-type sesquiterpenoids make up type VI, the last group. This class of compounds is very rare in Nature, and the first species of this chemotype is *P. swartziana*. Analysis of Colombian and Argentinean collections gave a wide range of africanes (92–96, 98, and 100–102), *seco*-africanes (103–105), and *nor-seco*-africanes (106 and 107) (126, 848). Apart from africanes, guaiane- (738, 739) and germacrane-type (e.g. 704) sesquiterpenoids have been isolated (40, 848). The presence of the same sesquiterpenoids 96, 98, 103, and 104 has been confirmed in the Japanese *P. subobtusa*. 14-Acetoxycaespitenone (97) has been also obtained (581). Unlike *P. swartziana*, *P. subobtusa* does not produce germacrane and guaiane, while the santalanes 891 and 893 and the monocyclofarnesanes 806 and 807 have been found (581). *P. subobtusa* is similar chemically to *P. caespitans* subsp. *setigera*, since both species produce africanes and santalanes (40).

The taxonomy of the genus *Porella* based on morphology has been regarded as notoriously difficult (722). Recent DNA-based studies have brought new insights to the phylogeny and taxonomy of these plants (335). Comparison of the molecular classification with recognized *Porella* chemotypes shows some striking

Table 8.2 Correlation between molecular classification and chemistry of *Porella* species (495)

Molecular classification based on maximum likelihood analysis (statistical support in brackets) (335)	Chemotype (495)
CLADE A1 (69%)	
<i>P. arboris-vitae</i>	I
<i>P. vernicosa</i>	I
<i>P. gracillima</i>	I
<i>P. obtusata</i>	I
<i>P. canariensis</i>	I
<i>P. roellii</i>	I
CLADE A2 (98%)	
<i>P. densifolia</i>	V
<i>P. stephaniana</i>	II
CLADE A3 (<50%)	
<i>P. japonica</i>	IV
CLADE A4 (<50%)	
<i>P. fauriei</i>	I
CLADE B1 (97%)	
<i>P. platyphylla</i>	III
<i>P. cordaeana</i>	V
<i>P. navicularis</i>	III
CLADE B2 (89%)	
<i>P. acutifolia</i>	IV
<i>P. camphylophylla</i>	II
<i>P. perrottetiana</i>	II
CLADE B3 (99%)	
<i>P. caespitans</i>	VI
<i>P. subobtusa</i>	VI
CLADE B4 (100%)	
<i>P. swartziana</i>	VI
CLADE B5 (81%)	
<i>P. grandiloba</i>	III

correlations (Table 8.2) (495). It appears that the distribution of chemotypes II, IV, and V over the molecular tree is scattered, but chemotypes I, III, and VI have more limited distributions and are phylogenetically informative. Thus, chemotypes III and VI occur only in species of lineage B, whereas the pungent chemotype I is exclusive to members of lineage A. In fact, all members of chemotype I (= the *Porella vernicosa* complex: *P. arboris-vitae*, *P. canariensis*, *P. obtusata*, *P. gracillima*, *P. roellii*, *P. vernicosa*), with the exception of *P. fauriei*, belong to the same molecular clade (A1). The chemical data suggest that the *Porella vernicosa* complex deserves recognition as a separate section of *Porella*, *Porella* section *Vernicosae* Ludwiczuk, Gradstein, Nagashima & Asakawa, *sect. nov.* Morphologically, the members of this section are recognized by the characteristic glossy color of the plants; other species of *Porella* are usually dull in color (495).

8.3.6.2 Lepidolaenaceae

Within the Lepidolaenaceae family, two *Gackstroemia* and four *Lepidolaena* species have been investigated chemically. From the ether extract of *G. decipiens*, the β -santalane-type sesquiterpenoids, **894–897**, together with (–)-13-hydroxy-*cis*-bergamota-3,11-diene (**275**), have been isolated (**252**). β -Santalene (**892**) has also been identified in *G. magellanica* together with some common mono- and sesquiterpenes (**40**). Santalanes are very rare in the Marchantiophyta, and, as mentioned in the previous section, they have been detected in *Porella navicularis* and *P. subobtusa*. Santalanes have been also found in some *Radula* and *Plagiochila* species (**32**, **223**).

In addition to santalanes and bergamotanes, *G. decipiens* also produces the rosane-type diterpenoids, **1337–1344**, together with 3-acetoxy-7,11-dihydroxy-farnesa-1,5,9-triene (**686**) and $1\beta,10\beta$ -epoxynardosin-7,11-diene (**832**) (**251**). Rosanes are new compounds for liverworts. Besides *Gackstroemia* species, they have been found together with pimaranes in *Porella navicularis* and *Plagiochila deltoidea* (**143**, **607**). β -Santalane-type sesquiterpenoids and rosane-type diterpenoids seem to be good chemical markers for *G. decipiens*.

A New Zealand specimen of *Lepidolaena clavigera* was found to produce polyoxygenated bergamotane sesquiterpenes with an unusual ring system, the clavigerins (**276–278**) (**72**, **656**, **657**). A very similar compound, **275**, has been reported in *Gackstroemia decipiens*. *L. clavigera* constitutes a link between *Gackstroemia* and *Lepidolaena* species.

Besides bergamotanes, which are good chemical marker of this species, the atisane diterpenoids, **1413** and **1414**, have been isolated from *L. clavigera* (**655**). These two compounds are characterized by an unprecedented level of oxidation of the atisane skeleton and are the first examples of such compounds in liverworts.

Three other *Lepidolaena* species, *L. hodgsoniae*, *L. taylorii*, and *L. palpebrifolia*, are chemically very different from *L. clavigera*. The former species are rich sources of the unusual hodgsonox-type sesquiterpenoids, **758–765** (**22**, **101**). Studies concerning the biosynthesis of hodgsonox (**758**) have revealed that it is formed exclusively by the MEP pathway (**100**). This is the only liverwort sesquiterpenoid known to be formed in this way.

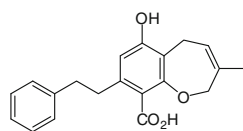
L. taylorii and *L. palpebrifolia* are chemically similar since both biosynthesize 8,9-*seco*-kauranes (**654**). Rabdoubrosanin (**1178**) and its epoxide (**1180**) are the main compounds isolated from both species. Together with 8,9-*seco*-kauranes, *L. taylorii* also produces kauranes. *ent*-16-Kauren-15-one (**1144**) and a series of C-7 and/or C-14 oxygenated derivatives of **1144** have been isolated (**654**).

8.3.6.3 Radulaceae

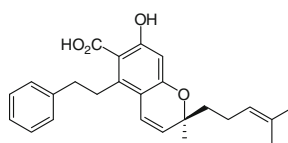
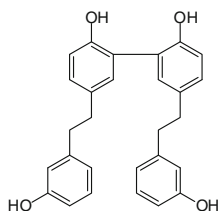
Radula, the only genus of the family Radulaceae, comprises about 150–200 species. It is an isolated taxon in the Jungermannioid group, and has been classified in the independent suborder Radulineae within the order Porellales (**168**, **169**).

The chemical constituents of *Radula* species are totally different from the other genera of the Marchantiophyta. Generally, they contain large amounts of bibenzyl derivatives. This liverwort genus is an extremely rich source of prenylated bibenzyls. Bibenzyls with a 2,2-dimethylchromene ring skeleton are also prevalent, especially compounds **1507** and **1509**. The most significant chemical indicators for *Radula* species are 3,5-dihydroxy-2-(3-methyl-2-butenyl)bibenzyl (**1525**) and 2-geranyl-3,5-dihydroxybibenzyl (**1530**).

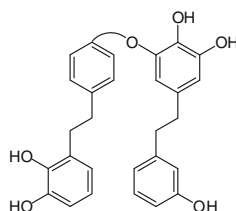
Apart from the two above-mentioned groups of bibenzyl derivatives, *Radula* species are also known for the presence of simple bibenzyls, bibenzyls with a dihydrooxepin skeleton, cyclopropanechroman derivatives, benzofurans, and bibenzyl cannabinoids. *R. javanica* is a rich source of bibenzyls possessing the dihydrooxepin skeleton, e.g. radulanins A (**1511**), C (**1512**), and E (**2203**) (39, 40). Related compounds have also been found in *R. appressa*, *R. buccinifera*, *R. complanata*, *R. constricta*, *R. grandis*, *R. javanica*, *R. lindenberghiana*, and *R. tokiensis* (39, 40, 294, 623). Usually, but not always, *Radula* species produce cyclopropanechroman derivatives together with bibenzyls possessing the dihydrooxepin skeleton. These compounds have been found in *R. constricta*, *R. grandis*, *R. javanica*, *R. lindenberghiana*, and *R. tokiensis* (39, 40). Besides the species mentioned, radulanins I (**1514**) and J (**1515**) have been detected in *R. obtusiloba*, *R. okamurana*, and *R. uvifera* (72, 623). *R. appressa* and *R. buccinifera* elaborate benzofurans together with dihydrooxepin compounds. 6-Hydroxy-4-(2-phenylethyl)benzofuran (**1519**) has been isolated from *R. appressa* (294). Compound **1519**, tylimanthin B (**1506**), and (2*R*)-isopropenyl-6-hydroxy-4-(2-phenylethyl)dihydrobenzofuran (**1520**) have been detected in *R. buccinifera* (72). Benzofurans have also been found in *R. kojana*, *R. laxiramera*, *R. oyamensis*, *R. perrottetii*, and *R. uvifera* (40, 623).



2203 (radulanin E)

2204 ((2*S*)-2-methyl-2-(4-methyl-3-pentenyl)-6-carboxy-7-hydroxy-5-(2-phenylethyl)chromene)

2205 (isoperrottetin A)



2206 (perrottetin H)

Radulanin E found in *Radula javanica*, a prenylethylchromene derivative from *R. kojana*, isoperrottetin A from *R. perrottetii*, and perrottetin H from *Jubula japonica* and the fern, *Hymenophyllum barbatum*

Interestingly, some *Radula* species produce bibenzyl cannabinoids. All cannabinoids isolated from *Radula* thus far belong to three types: (1) the *o*-cannabichromene-,

(2) *o*-cannabicyclol-, and (3) tetrahydrocannabinol- types, with the *o*-cannabichromene type as the most prevalent. *o*-Cannabichromene (**1534**) has been isolated from or detected in eight *Radula* species, *R. appressa*, *R. buccinifera*, *R. campanigera*, *R. javanica*, *R. kojana*, *R. lindenbergiana*, *R. obtusiloba*, and *R. tokiensis* (72, 294, 623). *R. kojana* also produces (2*S*)-2-methyl-2-(4-methyl-3-pentenyl)-6-carboxy-7-hydroxy-5-(2-phenylethyl)chromene (**2204**) (40). 5-Hydroxy-2-methyl-2-(4-methyl-3-pentenyl)-7-(2-phenylethyl)chromene (**1540**) has been isolated from *R. laxiramea* (178). *o*-Cannabicyclol (**1535**), which belongs to type II, has been found in *R. appressa* originating from Madagascar (294). From the Japanese *R. perrottetii*, perrottetinene (**1546**), belonging to the tetrahydrocannabinol type, has been isolated (40). After this finding, the same compound has been detected also in *R. campanigera*, *R. chinensis*, *R. laxiramea*, and *R. marginata* (178, 623, 895). The New Zealand *R. marginata* also produces perrottetinenic acid (**1545**), which belongs to the same class of bibenzyl cannabinoids (895).

Besides widespread bibenzyl derivatives, *Radula* species occasionally produce other compounds such as bis-bibenzyls. From *R. perrottetii* and *R. kojana*, the bis-bibenzyls, perrottetin E (**1638**) and perrottetin F (**1639**), have been isolated (40). The former species elaborates two additional compounds, perrottetin G (**1640**) and isoperrottetin A (**2205**) (40). Perrottetin E (**1638**) has been purified also from the Costa Rican liverwort, *R. laxiramea* (178). These three liverworts are chemically differentiated from the other *Radula* species.

The content of terpenoids in *Radula* species is generally very low. The exception to the rule is the Japanese *R. perrottetii*, which produces a large amount of bisabol-2,6,11-triene (**318**) (492). The presence of this compound, together with other bisabolanes in the essential oil prepared from the same species, has been confirmed (826). Analysis of the essential oil of *R. perrottetii* afforded the two viscidane diterpenoids, **1411** and **1412** (826). This is the only report of diterpenoids in *Radula* species, as well as viscidane-type diterpenoids in liverworts.

8.3.6.4 Frullaniaceae

With an estimated 300–375 species, *Frullania* is the largest genus of Porellales and forms a major clade of leafy liverworts (336). Eighty-three *Frullania* species have been chemically investigated. On the basis of their chemical composition, these species can be divided into seven major groups, namely, type I: sesquiterpene lactone-bibenzyl, type II: sesquiterpene lactone, type III: bibenzyl, type IV: labdane, type V: bazzanane, type VI: pacifigorgiane-type, and type VII: cyclocolorone (Table 8.3). As shown in this table, the most significant markers of *Frullania* species are sesquiterpene lactones and bibenzyls. Five types of sesquiterpene γ -lactones have been recognized in *Frullania* species. There are the eudesmanolides, elemanolides, eremophilanolides, germacranolides, and guaianolides, and, among these, the eudesmane-type sesquiterpene lactones are the most prevalent.

Frullania species belonging to the first chemotype produce sesquiterpene lactones and bibenzyls as the main components. Besides eudesmanolides, *F. muscicola* from the Azores Islands elaborates $4\beta,5\alpha,6\alpha,7\alpha$ -1(10),11(13)-

Table 8.3 Chemotypes of *Frullania* species

Type I (SL-BB)	Type II (SL)	Type III (BB)	Type IV (LAB)	Type V (BAZ)	Type VI (PAC)	Type VII (CYCLOCOL)	Other types
<i>F. brasiliensis</i>	<i>F. apiculata</i>	<i>F. amplicrania</i>	<i>F. fugax</i>	<i>F. falciloba</i>	<i>F. fragilifolia</i>	<i>F. diversitexta</i>	<i>F. clavata</i>
<i>F. convoluta</i>	<i>F. asagrayana</i>	<i>F. anomala</i>	<i>F. hamatiloba</i>	<i>F. squarrosula</i>	<i>F. tamarisci</i>	<i>F. gaudichaudi</i>	<i>F. kagoshimensis</i>
<i>F. daurica</i>	<i>F. aterritima</i> var. <i>aterrima</i>	<i>F. bonincola</i>		Unidentified	<i>F. tamarisci</i> subsp. <i>asagrayana</i>		<i>F. motoyana</i>
<i>F. daurica</i>	<i>F. bicornistipula</i>	<i>F. ericoides</i>		<i>Frullania</i> sp.			<i>F. solanderiana</i>
<i>F. dilatata</i>	<i>F. brotheri</i>	<i>F. jackii</i>					<i>F. taradakensis</i>
<i>F. dilatata</i> var. <i>anomala</i>	<i>F. californica</i>	<i>F. patula</i>					<i>F. truncata</i>
<i>F. incumbens</i>	<i>F. chevalierii</i>	<i>F. pedicellata</i>					
<i>F. muscicola</i>	<i>F. congesta</i>	<i>F. pycnantha</i>					
<i>F. osumiensis</i>	<i>F. densiloba</i>	<i>F. scandens</i>					
<i>F. parvistipula</i>	<i>F. deplanata</i>	<i>F. spinifera</i>					
<i>F. ptychantha</i>	<i>F. inflata</i>						
<i>F. serrata</i>	<i>F. lobulata</i>						
<i>F. tamarisci</i> subsp. <i>obscura</i>	<i>F. magellanica</i>						
<i>F. tamarisci</i> subsp. <i>tamarisci</i>	<i>F. media</i>						

(continued)

eremophiladiene-12,6-olide (**564**) ([443](#)). Eremophila-12,6-olides are very rare compounds and such lactones (**567**, **568**) have been detected also in the Bulgarian *F. dilatata* ([578](#)) and the Argentinean *F. brasiliensis* ([98](#)).

A specimen of *F. dilatata* obtained from Bulgaria proved to be very interesting because it produced not only eremophila-12,6-olides but also the rearranged spiroeudesmane-type sesquiterpenoids, **680–682** ([578](#)). Interestingly, a Japanese collection of *F. densiloba* elaborated the eudesm-12,8-olides, **651** and **652** ([589](#)). All eudesmanolides detected in *Frullania* species possess a 12,6-olide moiety. The finding of compounds **651** and **652** is the only exception to this observation.

Frullania muscicola is also known for the presence of dimeric sesquiterpene lactones and phthalides. Muscicolides A (**674**) and B (**675**) have been isolated from this species together with compounds **1808–1810** ([443](#)). Two other *Frullania* species, *F. tamarisci* subsp. *obscura* and *F. yunnanensis*, are known for the content of eudesmanolide dimers, while phthalide **1807** has been isolated from *F. falciloba* ([40](#), [78](#), [886](#)).

The Ecuadorian *Frullania convoluta* produces eudesmanolides, germacranolides, bibenzyls, and also bis-bibenzyls and acyclic bibenzyl-dihydrophenanthrenes ([226](#)). The latter two groups of compounds have been found only in this *Frullania* species. The isolated bis-bibenzyls, **1638–1641**, are perrottetin-type compounds and are widespread in the Radulaceae and Marchantiaceae liverwort families. The acyclic bibenzyl-dihydrophenanthrenes, **1558** and **1559**, seem to be good chemical markers of this liverwort. So far, only the similar compound **1560** is known as a constituent of *Cavicularia densa* ([875](#)). However, cavicularin (**1560**) is representative of the cyclic type of bibenzyl-dihydrophenanthrenes.

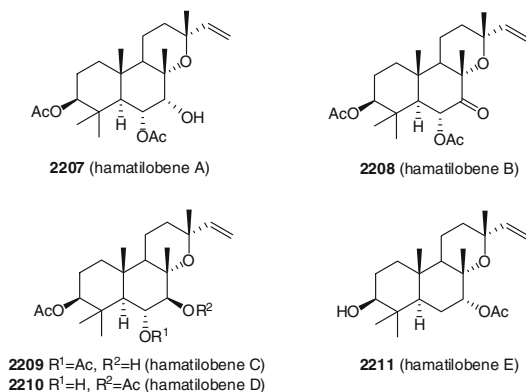
Frullania vethii, which was classified in chemotype II, produces guaianolides together with elemene-type sesquiterpene lactones ([39](#), [53](#)). Guaianolides have not been detected in the other *Frullania* species so far. This liverwort also produces a large amount of 5-hydroxy-7,4'-dimethoxyflavone (**1927**) ([39](#), [53](#)). This is exceptional, since liverworts belonging to the Frullaniaceae family usually produce flavone *O*-glycosides ([555](#)).

The New Zealand *Frullania chevalieri* (type II) elaborates eudesmane-type sesquiterpene lactones, with β -cyclocostunolide (**656**) and dihydro- β -cyclocostunolide (**657**) having been detected in this species ([78](#)). This is significant because the status of this species has remained controversial for some time. *Von Konrad* and coworkers reported that chemical and morphological evidence strongly supports the retention of *Frullania chevalieri* (not *Schusterella*) and its allies in the genus *Frullania* ([918](#)).

Frullania species classified in chemotype III do not produce sesquiterpene lactones at all, but these species are known for the presence of bibenzyls. Among ten liverworts classified in this chemotype, seven species elaborate bibenzyls possessing the methylenedioxy group; 3-methoxy-3',4'-methylenedioxybibenzyl (**1487**) is the most predominant ([39](#), [40](#), [78](#)).

Frullania hamatiloba and *F. fugax* represent the labdane chemotype (IV), since both species produce structurally similar labdane-type diterpenoids. Manoyl oxide (**1288**) has been isolated from *F. fugax* ([78](#)), while its derivatives, hamatilobenenes A-E **2207–2211**, have been found in *F. hamatiloba* ([40](#)). A second collection of *F. hamatiloba* was found to produce structurally different labdanes. Three labdane-type epoxides, **1309–1311**, have been isolated from this species together with the

fusicoccane-type diterpenoids **1098** and **1099** (316). These data suggest that there are two chemotypes of *F. hamatiloba* in Japan.



Hamatilobenes A-E, labdane-type diterpenoids found in *Frullania hamatiloba*

The New Zealand *Frullania falciloba* belongs to chemotype V of the Frullaniaceae, since it elaborates characteristic bazzanane-type sesquiterpenoids (**261**, **265**, **269**), with no sesquiterpene lactones having been detected (613). Bazzanenones A-D (**265**–**268**) have been isolated from an unidentified New Zealand *Frullania* species (72). The bazzanane sesquiterpenoids **261**, **262**, **268**, **270**, and **271** have been also found in *F. squarrosula* (78, 84).

Chemical analysis of the New Zealand *Frullania falciloba* from different collections showed the presence of β -bazzanene (**261**), but no other bazzananes were detected. This species produces 3-methoxy-3',4'-methylenedioxybiphenyl (**1487**), as the main component, along with the fusicoccane diterpenoid, fusicogigantepoxide (**1102**) (78). On the other hand, in an Australian specimen, a large amount of the monocyclofarnesane-type sesquiterpene hydrocarbon, striatene (**808**), together with fusicoccane-type diterpenoids (**1095**, **1102**), have been found to occur (78). It is worth mentioning that the presence of compounds **1095** and **1102** in *F. squarrosula* has also been confirmed (78). Further detailed analysis is required in order to investigate the chemical variations within *Frullania falciloba*.

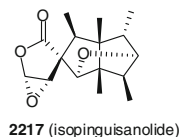
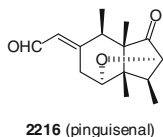
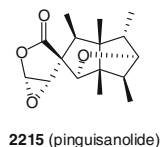
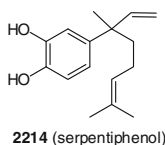
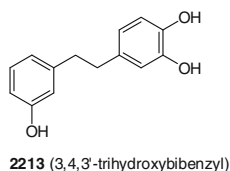
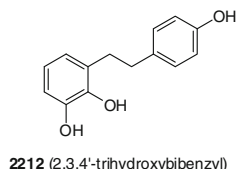
Type VI of *Frullania* species produces the pacifigorgiane-type sesquiterpenoids. (–)-Tamariscol (**833**), a pacifigorgiane alcohol, has been demonstrated to be the main component in the American *F. tamarisci* and *F. tamarisci* subsp. *asagrayana* (40, 644). It is noteworthy that a small amount of the same compound has also been isolated from *F. tamarisci* subsp. *tamarisci* (type I) and *F. nepalensis* (type II), while the (+)-enantiomer has been found in the European *F. tamarisci* subsp. *obscura* (type I) (40). Besides tamariscol (**833**), the American *F. tamarisci* produces other pacifigorgianes (**835**–**839**), together with the rearranged pacifigorgiane, tamariscene (**834**) (644). Tamariscene (**834**) is the major constituent of the German *F. fragilifolia*, and the pacifigorgianes **835**–**839** have also been found (644).

Frullania diversitexta (type VII) produces a large amount of cyclocolorenone (**126**), an aromadendrane sesquiterpene ketone, together with other common sesquiterpenoids like the bicyclogermacrene, γ -gurjunene, or α - and β -cubebene and fusicoccane-type diterpenoids (**1095**, **1102**) ((53); *Ludwiczuk*, unpublished data). Neither sesquiterpene lactones nor bibenzyls were present in *F. diversitexta*. The second liverwort belonging to this chemotype is *F. gaudichaudii*, which is chemically very similar to *F. diversitexta* (55). Cyclocolorenone (**126**) has been found in several *Porella* species belonging to chemotype I of the Porellaceae (see Sect. 8.3.6.1).

There are a few other *Frullania* species difficult to classify in terms of the seven chemotypes indicated above, and further chemical analysis will be necessary. However, among these species, the New Zealand *F. solanderiana* produces very characteristic 2-alkanones, such as 2-undecanone (**1955**), 2-tridecanone (**1956**), and 2-pentadecanone (**1959**), as the main components (78). This is the first record of the identification of the 2-alkanones in the genus *Frullania*.

8.3.6.5 Jubulaceae

Jubula japonica produces the acyclic bis-bibenzyl, perrottetin H (**2206**), as the major constituent, together with bibenzyls and sesquiterpenoids (39, 858). Chemical analysis has led to the identification of 3-methoxy-4'-hydroxybibenzyl (**1482**), 2,3,4'-trihydroxybibenzyl (**2212**), and 3,4,3'-trihydroxybibenzyl (**2213**). The latter two compounds are the building blocks of perrottetin H (**2206**) (39, 45). Among the sesquiterpenoids, cyclocolorenone (**126**), malioxide (**722**), β -elemene (**283**), 2-cuparenol (**483**), and an unstable humulane sesquiterpenoid have been detected (39, 858). It is noteworthy that perrottetin H (**2206**) has been found in the Japanese fern, *Hymenophyllum barbatum* (633).



Bibenzyl derivatives found in *Jubula japonica*, serpentiphenol from *Cheilolejeunea serpentina*, and pinguisanolides and pinguisenal from *Prilidium pulcherrimum*

Cuparene (464) and 2-cuparenol (483) are the main components of *J. hutchinsiae* subsp. *javanica*, but this species does not biosynthesize bibenzyls and bis-bibenzyls (45).

The genera *Frullania* and *Jubula* have been included in the same family, Jubulaceae, for a long time (167). In recent classifications of the Marchantiophyta, both genera were placed in the independent families (168, 169). Phytochemical data obtained thus far support this new classification.

Apart from *Jubula* species, the Jubulaceae comprises one additional genus, *Nipponolejeunea*, which was moved from the family Lejeuneaceae (168, 169). The genus *Nipponolejeunea* is endemic to Japan and contains two species, *N. pilifera* and *N. subalpina*. Chemical analysis of these two species has revealed that both produce mainly monoterpenoids, and borneol (57) together with bornyl acetate (58) are the main components (264). These two compounds are responsible for the fragrant odor of these liverworts. The presence of borneol (57) and bornyl acetate (58) has clearly underlined the difference between the genus *Nipponolejeunea* and other members of the family Lejeuneaceae, since these compounds have not yet been detected in any other genera. However, there is no chemical relationship between *Jubula* and *Nipponolejeunea*.

8.3.6.6 Lejeuneaceae

The Lejeuneaceae is the largest family of the liverworts, with almost 1,000 species in 91 currently accepted genera (267). Recent phylogenetic studies have revealed that the Ptychanthinae (*Bryopteris*, *Ptychanthus*, *Schiffneriolejeunea*, *Thysananthus*) and Acrolejeuneinae (*Acrolejeunea*, *Frullanoides*, *Trocholejeunea*, *Archilejeunea*) clades occur in the Ptychanthoideae subfamily, and the Brachiolejeuneinae (*Dicranolejeunea*, *Blepharolejeunea*) and Lejeuneinae (*Cheilolejeunea*, *Omphalanthus*, *Drepanolejeunea*, *Lejeunea*) clades in the Lejeuneoideae subfamily of the Lejeuneaceae (267).

Based on the chemical composition of the species belonging to the Lejeuneaceae family, it may be concluded that liverworts from the Ptychanthinae, Acrolejeuneinae, and Brachiolejeuneinae clades are rich sources of pinguisane-type sesquiterpenoids, but pinguisanin (874) and dehydropinguisanin (875) appear to be chemical markers of the *Acrolejeunea* complex. These two compounds are the main constituents detected in *Acrolejeunea* species, *Trocholejeunea sandvicensis*, and *Frullanoides densifolia*. On the other hand, pinguisone (857), norpinguisone methyl ester (861), pinguisenene (867), and *neo*-pinguisenol (842) seem to be good markers of the Ptychanthinae and Brachiolejeuneinae clades (40, 265, 869). Norpinguisone methyl ester (861), which is the main component of *Bryopteris filicina*, is also the only norpinguisone so far detected in the Lejeuneaceae family (39, 576, 604). It is noteworthy that compound 870 and other norpinguisones are very common compounds in the genus *Porella*.

Pinguisenene (867) has been detected as the main compound in *Ptychanthus striatus* and *Thysananthus fruticosus*, while pinguisone (857) has been found only

in *Blepharolejeunea securifolia* (40, 265). A large amount of the very characteristic alcohol, *neo-pinguisenol* (842), has been isolated from *Dicranolejeunea yoshinagana* (869).

The Lejeuneaceae family is also characterized by the presence of the monocyclofarnesane-type sesquiterpenoids, 805 and 808–810. Liverworts classified in the Phychanthinae clade, in particular, are a rich source of these compounds. Additionally, some genera belonging to the Lejeuneaceae, such as *Cheilolejeunea*, *Lejeunea* and *Diplasiolejeunea* also produce these compounds. The monocyclofarnesanes have not been detected in the Acrolejeuneinae and Brachiolejeuneinae clades (39, 40). The distribution of pinguisane- and monocyclofarnesane-type sesquiterpenoids in the Lejeuneaceae supports the classification of this family proposed by Gradstein and associates (267). The liverworts classified in the Lejeuneaceae often produce particular compounds characteristic for each species or genus.

Trocholejeunea sandvicensis produces a large amount of pinguisanes, which are the most significant chemical markers of this species (45, 85). It contains a wide range of these compounds, among which pinguisanin (874) and dehydropinguisenol (868) are the main components (40, 492). It is worthy of note that lejeuneapinguisanolide (852), isolated from *T. sandvicensis*, is chemically quite similar to porellapinguisanolide (853) found in *Porella cordaeana* and *P. platyphylla* (138, 460, 863). *Frullanoides densifolia* is also chemically very close to *Porella* species, especially to *Porella japonica* and *P. acutifolia* subsp. *tosana*, because in these species pinguisanes and guaiane-type sesquiterpene lactones have been found (40) (see Sect. 8.3.6.1). The presence of such secondary metabolites in two different families suggests that they may originate from the same ancestor.

Chemosystematically, it is very interesting to observe that *T. sandvicensis* produces trifarane-type sesquiterpenoids. (–)-Trifara-9,14-diene (911), (–)-3,7-diepi-trifara-9,14-diene (912), (+)-neotrifaradiene (913), and a biogenetically related compound possessing a new skeleton, (+)-sandvicene (919), have been isolated from this liverwort (539). The trifaranes, 906–910, have been isolated from *Cheilolejeunea trifaria* (306, 309). Thus, *T. sandvicensis* and *C. trifaria* are closely related chemically.

Trifaranes have not been found in other *Cheilolejeunea* species. Chemical analysis has shown that all investigated *Cheilolejeunea* species produce monocyclofarnesanes (*C. trifaria*, *C. serpentina*, *C. excisula*, and *C. imbricata*) (40, 854). These compounds seem to be good generic markers. However, *C. serpentina* and *C. imbricata* are chemically quite different from the other *Cheilolejeunea* species. The former species produces the very characteristic phenolic sesquiterpenoid, serpentiphenol (2214) (40), while two δ -lactones with a strong milky-like fragrance, (*R*)-dodec-2-en-1,5-olide (1946) and (*R*)-tetradec-2-en-1,5-olide (1947), have been isolated from the latter species (879).

The Costa Rican, *Bryopteris filicina*, produces the norpinguisone methyl ester (861) as the main component (604). This was isolated previously from a Panamanian collection of the same species (576). Germacrane, lepidozanes, and humulanes have also been found in this species together with the fusicoccane

diterpenoids, fusicogigantepoxide (**1102**) and anadensin (**1105**), and the bis-bibenzyl, isomarchantin C (**1592**) (576, 604). *B. filicina* resembles the genus *Ptychanthus* morphologically and both are classified in the Ptychanthinae clade within the Lejeuneaceae (267). Since *P. striatus* produces pinguisane-type sesquiterpenoids such as **862**, **867**, and **890** (40), bis-bibenzyls structurally similar to isomarchantin C (**1592**), and ptychantols A-C (**1649–1651**) (320), these species are both morphologically and chemically closely related.

The most characteristic chemical markers of *Ptychanthus striatus* are labdane-type diterpenoids. This liverwort produces a wide range of the highly oxygenated labdanes, ptychantins A-Q (**1245–1261**) (305, 308, 320, 324, 325, 399, 957). The labdane-type diterpenoids have also been detected in *Tuzibeanthus* species. These two genera are closely related chemically since they also share the same pinguisanes and monocyclofarnesanes (265).

Archilejeunea olivacea biosynthesizes β -monocyclonerolidol (**805**) and the biogenetically related sesquiterpene hydrocarbon, olivacene (**927**), which has not been found in any Lejeuneaceae species (879).

From the Madagascan *Thysananthus spathulistipus*, two clerodane diterpenoids, **986** and **987**, have been isolated (294). Clerodane-type diterpenoids from species in the family Lejeuneaceae are very rare. As far as we are aware, only one example of the isolation of kolavelool (**967**) has been reported from *Macrolejeunea pallescens* (= *Lejeunea pallescens*) (40).

Leptolejeunea elliptica grows on tea leaves and ferns and emits a very characteristic odor when crushed, attributable to 1-ethyl-4-hydroxybenzene (**1796**) and its methyl (**1797**) and acetyl (**1798**) derivatives, which have not yet been detected in any other liverworts so far examined (879). These compounds are valuable chemical markers of this species.

The Colombian liverwort, *Omphalanthus filiformis*, is quite characteristic chemically, since it elaborates chamigrane-type sesquiterpenoids. β -Chamigrene (**436**), chamigrenic acid (**441**), and the rearranged chamigrane-type sesquiterpenoid, omphalic acid (**443**), have been isolated from this species together with 5-heptadeca-(8Z,11Z,14Z)-trienylresorcinol (**1873**) (844).

Lejeunea aquatica, *L. flava*, and *L. japonica* commonly produce cuparane sesquiterpenoids (878). For all three species, 2-cuparenol (**483**), 1,2-cuparenediol (**487**), and 1,4-cuparenediol (**488**) have been detected. Interestingly, *L. aquatica* additionally elaborates the cuparane dimer, aquaticenol (**491**), along with the gymnomitrane sesquiterpenoids, β -barbatene (**235**), and 3-gymnomitren-15-ol (**237**) (878). The cuparanes are very rare in the Lejeuneaceae and are suggested to be very important chemical indicators of the genus *Lejeunea*.

The *Marchesinia* species are chemically very different from the other liverwort species classified in the Lejeuneaceae, because they biosynthesize styrenes, allyl benzenes, and stilbene derivatives as the major components. The Ecuadorian *M. brachiata* elaborates 3,4-dimethoxystyrene (**1672**) and 2,4,5-trimethoxystyrene (**1673**) (594). Compound **1672** is distributed in *Conocephalum conicum* and *Asterella*-like species, which belong to the Marchantioid group of the liverworts (71, 880). In the essential oil of the European *M. mackaii*, alkylbenzenes

1673–1678 together with a few widely distributed sesquiterpenoids have been detected (220). 3,4-Dihydroxy-3'-methoxy-(*E*)-stilbene (**1490**) has been isolated from the Colombian *M. bongardiana* (765). There is no chemical affinity between these three *Marchesinia* species.

8.3.7 Order Ptilidiales

8.3.7.1 Ptilidiaceae

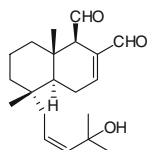
The most significant chemical markers of the Ptilidiaceae are pinguisane-type sesquiterpenoids. Krutov and associates (450) isolated deoxopinguisone (**862**) from the Czech *Ptilidium ciliare*. Deoxopinguisone (**862**) and pinguisanin (**874**), together with bicyclogermacrene (**293**) and β -caryophyllene (**426**), have been detected in the same species collected in Finland (596). Pinguisanin (**874**) and pinguisanolide (**2215**) are the main components isolated from the French *P. pulcherrimum*. Besides these two compounds, pinguisenal (**2216**), isopinguisanolide (**2217**), and β -caryophyllene (**426**) have been also detected (52). The pinguisanes mentioned above have been also found in *Porella* species (Porellaceae) and *Tricholejeunea sandvicensis* (Lejeuneaceae) (40). Surprisingly, in the Chinese *P. pulcherrimum*, a wide range of triterpenoids and aromatic compounds has been detected (271). This liverwort produces norlupanes (**1466**) and ursane-type diterpenoids (**1467–1471**), together with several aromatic compounds like orsellinic acid methyl ester (**1729**) and ethyl ester (**1730**), isovanillin (**1726**), methyl 2,4-dihydroxybenzoate (**1728**), and pulcherrimumin (**1731**) (271). It is worth noting that orsellinates have been found in lichens and a few liverworts, such as *Blasia pusilla* and some *Frullania* species (78, 84, 971).

8.3.7.2 Neotrichocoleaceae

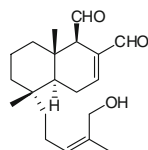
The Neotrichocoleaceae family comprises two genera, *Neotrichocolea* and *Trichocoleopsis*. In the new classification of the Marchantiophyta proposed by Crandall-Stotler and colleagues (168, 169), both genera have been removed from the family Trichocoleaceae in the order Jungermanniales and placed into the independent family Neotrichocoleaceae in the order Ptilidiales.

Neotrichocolea bissetii elaborates predominantly pinguisanin (**874**), together with pinguisanolide (**2215**), *ent*-bicyclogermacrene (**293**), *ent*-globulol (**139**), drimenol (**538**), cuparene (**464**), and β -elemene (**283**) (39, 40, 891). Two pinguisane-type sesquiterpenoids have been also detected in *Trichocoleopsis sacculata*, namely, pinguisone (**857**) and deoxopinguisone (**862**) (39). However, the most characteristic compounds of this liverwort species are sacculatane-type diterpenoids. The pungent sacculatal (**1348**) and its C-9 isomer (**1349**), together

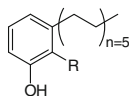
with 18-hydroxysacculatal (**2218**) and 19-hydroxysacculatal (**2219**), have been isolated (**39**).



2218 (18-hydroxysacculatal)

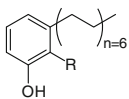


2219 (19-hydroxysacculatal)



2220 R=CO₂H (6-undecyl salicylic acid)

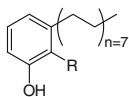
2221 R=CO₂K (potassium 6-undecyl salicylate)



2222 R=H (3-tridecylphenol)

2223 R=CO₂H (6-tridecyl salicylic acid)

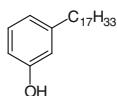
2224 R=CO₂K (potassium 6-tridecyl salicylate)



2225 R=H (3-pentadecylphenol)

2226 R=CO₂H (6-pentadecyl salicylic acid)

2227 R=CO₂K (potassium 6-pentadecyl salicylate)



2228 (3-heptadecylphenol)

Sacculatane type diterpenoids found in *Trichocoleopsis sacculata* and alkylphenols from *Schistochila appendiculata*

On the basis of the above information, pinguisane-type sesquiterpenoids seem to be good chemical markers of the liverworts belonging to the order Ptilidiales, since both families are characterized by the presence of these compounds. The exclusion of the genera *Neotrichocolea* and *Trichocoleopsis* from the Trichocoleaceae is substantiated on a chemical basis. The genus *Trichocolea* is quite different chemically from the above-mentioned taxa, because of the presence of various methyl benzoates with prenyl ether moieties (see Sect. 8.3.8.4). Such compounds have not been found in *Neotrichocolea* and *Trichocoleopsis* species.

8.3.8 Order Jungermanniales

8.3.8.1 Schistochilaceae

Among five genera classified in the family Schistochilaceae, only two have been analyzed chemically, *Paraschistochila* and *Schistochila*. The New Zealand

Paraschistochila pinnatifolia produces *ent*-1 β -hydroxykauran-12-one (**1166**) as the main component (**483**). The chemical composition of *P. pinnatifolia* from different collections showed the presence of an additional kaurane diterpenoid, *ent*-12 β -hydroxykaurane (**1167**), together with the sacculatane-type diterpenoids, perrottetianal A (**1354**) and 8(12),17-sacculatadien-11,13-olide (**1375**) (**84**). *P. pinnatifolia* is chemically very distinct from the other *Paraschistochila* and *Schistochila* species investigated thus far.

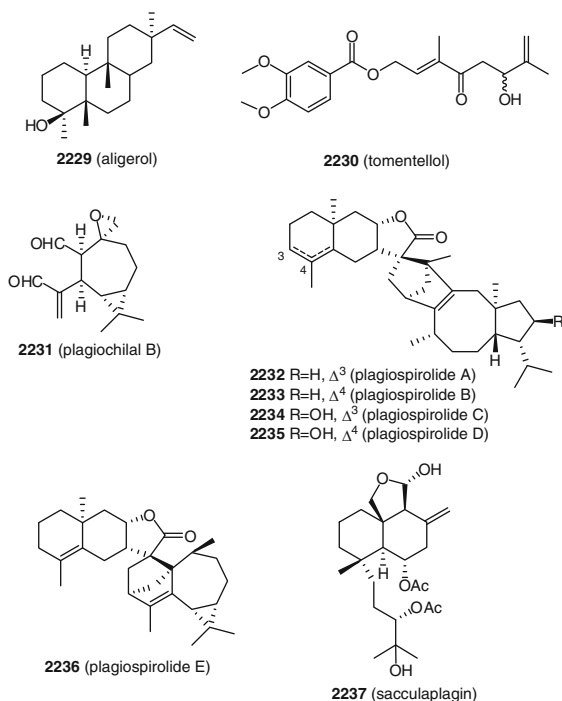
Paraschistochila tuloides elaborates sesquiterpenoids, and, among these, aromadendranes are the most prevalent. The presence of α -gurjunene (**123**), β -gurjunene (**124**), cyclocolorenone (**126**), and spathulenol (**136**) was confirmed (**72**). β -Gurjunene (**124**) has been detected as the major component of two *Schistochila* species, *S. bafouriana* and *S. repleta*. The former species produces the same aromadendrane sesquiterpenoids as were detected in *P. tuloides* (**72**). The rest of the *Schistochila* species investigated produce their own particular compounds, and, because of this, they are very different from one another, as discussed below.

Schistochila appendiculata is characterized by the presence of compounds that cause strong allergenic contact dermatitis. These are the long-chain alkylphenols, 3-undecyl- (**1874**), 3-tridecyl- (**2222**), 3-pentadecyl- (**2225**), and 3-heptadecyl (**2228**) phenol, the long-chain alkyl salicylic acid derivatives, 6-undecyl- (**2220**), 6-tridecyl- (**2223**), and 6-pentadecyl (**2226**) salicylic acid, and their potassium salts, potassium 6-undecyl- (**2221**), 6-tridecyl- (**2224**), and 6-pentadecyl (**2227**) salicylate, as well as 6-undecyl catechol (**1875**) (**40, 46, 488**).

Schistochila glaucescens elaborates the macrocyclic bis-bibenzyls, neo-marchantins A (**1595**) and B (**1596**), along with marchantin C (**1579**) and two bis-bibenzyls connected to a sesquiterpene moiety (**1658, 1659**) (**607, 712**). These aromatic compounds have not been isolated from other *Schistochila* species, and thus they are valuable chemical markers of *S. glaucescens*. Besides aromatic compounds, this liverwort produces sesquiterpenoids. Striatene (**808**) and a new sesquiterpene lactone, glaucescenolide (**931**), have been isolated (**72, 712**). Compound **931** is the first example of sesquiterpene lactone in the genus *Schistochila*.

Schistochila nobilis and *S. acuminata* are known for the presence of cyathane-type and clerodane-type diterpenoids. However, the compounds occurring in each species are different. *S. acuminata* produces homoverrucosanes and neoverrucosanes, while in *S. nobilis*, 13-*epi*-homo- and 13-*epi*-neoverrucosanes have been found (**40, 635**). The other chemical distinction recognized between these two species is the presence of schistochilic acid A (**992**), a *seco*-clerodane-type diterpenoid in *S. nobilis* (**40, 635**). The *seco*-clerodanes are very rare among the liverworts. Besides *S. nobilis*, such compounds have been detected only in *Scapania nemorea* (**253, 569**).

Like the two *Schistochila* species mentioned, *S. alligera* produces clerodane-type sesquiterpenoids of the *cis*-series. However, the most characteristic compound of this species is the rearranged pimarane-type diterpenoid, aligerol (**2229**) (**40**).



A pimarane-type diterpenoid found in *Schistochila alligera*, a prenyl benzoate from *Trichocolea mollissima*, a 2,3-secoaromadendrine-type sesquiterpene aldehyde from *Plagiochila* species, eudesmane/fusicothane dimers and a eudesmane/aromadendrane dimer from *Plagiochila moritziana*, and a sacculatane-type diterpene from *Plagiochila sciophila*

8.3.8.2 Herbertaceae

The family Herbertaceae consists of the genera *Herbertus*, *Triandrophyllum*, and *Olgantha*, with species belonging to the first two of these genera having been investigated chemically.

Triandrophyllum subtrifidum var. *trifidum* produces calamenanes, calamenene (**403**), 5-hydroxycalamenene (**406**) and β -calacorene, together with (–)- α -formylherbertenol (**515**), 2-cuparenol (**483**), and other sesquiterpenoids (**40**).

Compounds **483** and **515**, along with a number of the other herbertane- and cuparane-type sesquiterpenoids, have been isolated from Japanese, Indian, and Scottish collections of *Herbertus aduncus* (**40**, **137**, **323**). *H. aduncus* is chemically very similar to *H. sakuraii*, since both produce the same herbertanes (e.g. **487**, **512**, **520**, **524**), although the latter species additionally elaborates dimeric sesquiterpenoids and cyclic bis-bibenzylyls, which have not been found in *H. aduncus* (**321**, **323**, **365**). Mastigophorenes A–C (**528**–**530**) along with isoplagiochin C (**1606**), isoplagiochin D (**1607**), and the chlorinated derivatives of the above-mentioned bis-bibenzylyls, **1613**–**1615**, have been isolated from the Japanese *H. sakuraii* (**321**, **323**, **365**).

H. sakuraii is very similar chemically to *Mastigophora diclados* (Mastigophoraceae), since both species produce herbertane dimers and bis-bibenzyls (see Sect. 8.3.8.3).

Herbertane-type sesquiterpenoids are significant chemical markers of the family Herbertaceae. Besides the species mentioned, herbertanes have been found as the main components in *H. acantheliius*, *H. borealis*, *H. divergens*, and *H. subdeanthus* (40, 137).

The New Zealand *H. alpinus* is quite distinct chemically from the other *Herbertus* species. The main compound that occurs is labda-8(17),(12E),14-trien-6 α -ol (1235) (72), while *ent*-3 β -hydroxy-8(17),(12E),14-labdatriene (1236) and *ent*-3 β -hydroxy-16-kaurene (1140) have also been isolated from this species. *H. alpinus* does not biosynthesize herbertane-type sesquiterpenoids (558), with this being the only report of the presence of labdanes and kauranes in *Herbertus* species. However, the pimarane-type diterpenoid, *ent*-pimara-8(14),15-dien-19-oic acid (1325), has been isolated from *H. sakuraii* (323, 365).

8.3.8.3 Mastigophoraceae

The genera *Dendromastigophora* and *Mastigophora*, members of the Mastigophoraceae family, are very closely related chemically to *Herbertus* species (Herbertaceae). *Dendromastigophora* as well as *Mastigophora* species produce herbertane-type sesquiterpenoids as the main components.

Mastigophora diclados and *M. woodsii* elaborate herbertene (508), α - (509) and β -herbertenol (511), and herbertene-1,2-diol (512) (40). Besides these compounds, *M. diclados* from Madagascar biosynthesizes also mastigophoric acid methyl ester (516), herbertane dimers (530, 531), riccardin C (1566), and pimarane diterpenoids (1325, 1332) (287). The same pimarane-type diterpenoids (1325, 1332), together with herbertanes, have been found in a Taiwanese sample (40). A Japanese collection elaborated herbertene (508) and α -herbertenol (509), together with cyclic chlorinated bis-bibenzyls (1612, 1613), but no diterpenoids and herbertane dimers were detected (321). In the East Malaysian *M. diclados*, herbertanes (508–512) and mastigophorenes A–D (528–531) have been found (67). However, a West Malaysian specimen did not produce any herbertanes, with instead the trachylobane-type diterpenoids, 1388–1390, biogenetically related to the pimaranes, having been isolated (464). Trachylobanes are very rare in Nature and only one example of such compounds has been reported from *Jungermannia exsertifolia* subsp. *cordifolia* (298, 717). These data suggest that there are at least three geographical races of *M. diclados*: the bis-bibenzyl-type in Japan, the mastigophorene-type in Borneo (East Malaysia), and the pimarane and pimarane-derived trachylobane diterpenoid type in Taiwan and West Malaysia. Interestingly, all three types have been found in a Madagascan sample of *M. diclados*.

The chemical composition of *Dendromastigophora flagellifera* resembles those of the *Mastigophora* species. Apart from herbertanes, this species also produces diterpenoids. *ent*-Pimara-8(14),15-dien-19-oic acid (1325), which has been detected in *M. diclados* and *H. sakuraii*, has been isolated from *D. flagellifera*, together with 13-*epi*-neoverrucosan-5 β -ol (1056) (72, 635). The chemical

similarities between the Mastigophoraceae and Herbertaceae suggest that both families might originate from a common ancestor.

8.3.8.4 Trichocoleaceae

The genus *Trichocolea* is of nearly worldwide distribution. It is best represented in the tropics, while only a single species is known from the North Temperate Zone (327). *Trichocolea* species (*T. hatcheri*, *T. lanata*, *T. mollissima*, *T. pluma*, *T. tomentella*), collected in Japan, Taiwan, New Zealand, East Malaysia, and French Polynesia, have been investigated chemically. All studied specimens produce methyl benzoates with a prenyl ether group and these compounds are significant chemical markers of the genus *Trichocolea*.

Trichocolein (1747), tomentellin (1748), and (*E*)-isotomentellin (1749), together with the simple vanillic acid methyl ester, 1746, have been detected in the East Malaysian and Tahitian *T. pluma* (490, 494). In the volatile oil of *T. pluma* originating from Taiwan, besides trichocolein (1747), Chang and Wu detected the labdane-type diterpene alcohol, *ent*-3 α -hydroxyabda-8(17),(12*E*),14-triene (1236) (153). Diterpenoids are very rare among plants in the family Trichocoleaceae. Among *Trichocolea* species so far investigated, diterpenoids of the isopimarane series have been isolated only from the New Zealand *T. mollissima* (483, 605). Tomentellin (1748), (*E*)-isotomentellin (1749), and its (*Z*)-isomer (1750), along with the alcohol, tomentellol (2230), have been also detected in *T. mollissima* (40, 653). Compound 1747 has been found in *T. lanata* (72), while compounds 1748 and 1750 along with the 3'-hydroxymethyl benzoates, 1754–1758, have been isolated from *T. hatcherii* (91). The Japanese *T. tomentella* elaborates tomentellin (1748), (*Z*)-isotomentellin (1750) deoxytomentellin (1751), demethoxytomentellin (1752), and isohydroperoxytomentellin (1753) (40, 653).

8.3.8.5 Plagiochilaceae

Plagiochila is the largest genus in the Marchantiophyta, with at least 1600 species. *Plagiochila* exhibits a nearly unmanageable phenotypic variation, making it sometimes impossible to find two populations with an identical morphology (332). This genus is characterized not only by morphological diversity but also great chemical diversity. Up to the present, more than 90 *Plagiochila* species have been investigated chemically. Two main groups of the *Plagiochila* species have been recognized, namely, *Plagiochila* species characterized by either the presence or absence of 2,3-*seco*-aromadendrane-type sesquiterpenoids. For both groups, several chemotypes can be distinguished. As shown in Table 8.4, *Plagiochila* species (Fig. 8.3) have been classified into 12 chemotypes, namely, the I: 2,3-*seco*-aromadendrane-, II: 2,3-*seco*-aromadendrane-diterpenoid-, III: 2,3-*seco*-aromadendrane-gymnomitrane-, IV: diterpenoid-bis-bibenzyl-, V: diterpenoid-, VI: bibenzyl-, VII: bibenzyl-diterpenoid-, VIII: bibenzyl-bis-bibenzyl-, IX:

Table 8.4 Recognized chemotypes of *Plagiochila* species

<i>Plagiochila</i> species with the presence of 2,3- <i>seco</i> -aromadendranes					
Type I (2,3- <i>seco</i> ARO)*	Type II (2,3- <i>seco</i> ARO + DIT)	Type III (2,3- <i>seco</i> ARO + GYM)			
<i>P. adiantoides</i>	<i>P. ericicola</i>	<i>P. magna</i>	<i>P. aerea</i>	<i>P. trabeculata</i>	
<i>P. asplenoides</i>	<i>P. falcata</i>	<i>P. micropterix</i>	<i>P. cristata</i>		
<i>P. atlantica</i>	<i>P. fruticosa</i>	<i>P. orbicularis</i>	<i>P. moritziana</i>		
<i>P. beskeana</i>	<i>P. gayana</i>	<i>P. pittieri</i>	<i>P. ovalifolia</i>		
<i>P. carringtonii</i>	<i>P. goebeliana</i>	<i>P. porelloides</i>	<i>P. peculiaris</i>		
<i>P. cipaconensis</i>	<i>P. guayrapurinensis</i>	<i>P. satoi</i>	<i>P. pulcherrima</i>		
<i>P. cristatissima</i>	<i>P. guilleminiana</i>	<i>P. scopulosa</i>	<i>P. yokogurensis</i>		
<i>P. cucullata</i>	<i>P. hattoriana</i>	<i>P. semidecurrens</i>			
<i>P. dilatata</i>	<i>P. hookeriana</i>	<i>P. squamulosa</i> var. <i>sinuosa</i>			
<i>P. dura</i>	<i>P. incurvicola</i>	<i>P. tenerrima</i>			
<i>P. elegans</i>	<i>P. lecheri</i>				
<i>Plagiochila</i> species with the absence of 2,3- <i>seco</i> -aromadendranes					
Type IV (DIT + BBB)	Type V (DIT)	Type VI (BB)	Type VII (BB + DIT)	Type VIII (BB + BBB)	Type IX (PIN)
					Type X (CUP)
					Type XI (SL)
					Type XII (EVEA + DIPHE)
<i>P. barteri</i>	<i>P. circinalis</i>	<i>P. arbuscula</i>	<i>P. spinulosa</i>	<i>P. permista</i> var.	<i>P. alternans</i>
					<i>P. bispinosa</i>
<i>P. sciophila</i>	<i>P. corrugata</i>	<i>P. buchtiniana</i>	<i>P. stephensoniana</i>	<i>P. integerrima</i>	<i>P. hondurensis</i>
	<i>P. deltoidea</i>	<i>P. chacabucensis</i>			<i>P. duricaulis</i>
	<i>P. dusenii</i>	<i>P. diversifolia</i>		Unidentified I	<i>P. retrospectans</i>
	<i>P. geniculata</i>	<i>P. exigua</i>			<i>P. killarniensis</i>
					<i>P. retrorsa</i>
					<i>P. stricta</i>

(continued)

Table 8.4 (continued)

<i>Plagiochila</i> species with the presence of 2,3- <i>seco</i> -aromadendranes			
Type I (2,3- <i>seco</i> ARO)*	Type II (2,3- <i>seco</i> ARO + DIT)	Type III (2,3- <i>seco</i> ARO + GYM)	
<i>P. panamensis</i>	<i>P. fasciculata</i>		
<i>P. validissima</i>	<i>P. fuegiensis</i>		
Unidentified II	<i>P. gymnocalycina</i>		
	<i>P. longispina</i>		
	<i>P. maderensis</i>		
	<i>P. rutilans</i>		
	<i>P. standleyi</i>		
	<i>P. trichostoma</i>		
Other <i>Plagiochila</i> species			
<i>P. acanthola</i>	<i>P. elata</i>	<i>P. oresitropha</i>	<i>P. suborbiculata</i>
<i>P. amazonica</i>	<i>P. engelii</i>	<i>P. oxyphylla</i>	<i>P. tabinensis</i>
<i>P. bursata</i>	<i>P. excisa</i>	<i>P. pachyloma</i>	<i>P. tambillensis</i>
<i>P. cornicula</i>	<i>P. jamesoni</i>	<i>P. parvidens</i>	<i>P. terebrans</i>
<i>P. dendroides</i>	<i>P. kroneana</i>	<i>P. parvitexta</i>	<i>P. verruculosa</i>
<i>P. dichotoma</i>	<i>P. neesiana</i>	<i>P. pavidens</i>	

*2,3-*sec*-ARO 2,3-*seco*-aromadendranes, *DIT* diterpenoids, *GYM* gymnomitranes, *BBB* bis-bibenzylyls, *BB* bibenzylyls, *PIN* pinguisanes, *CUP* cuparanes, *SL* sesquiterpene lactones, *EVEA* everminic acid methyl ester, *DIPHE* 9,10-dihydrophenanthrenes

Fig. 8.3 *Plagiochila vincentina*. (Permission for the use of this figure has been obtained from Prof. Dr. Rob Gradstein, Paris, France)



pinguisane-, X: cuparane-, XI: sesquiterpene lactone-, and XII: everninic acid methyl ester-9,10-dihydrophenanthrene- types.

Among the *Plagiochila* species containing 2,3-*seco*-aromadendranes, certain species have been found to be very pungent. These produce plagiochiline A (**183**), which may be degraded enzymatically to give two pungent components, furanoplagiochilal (**212a**) and plagiochilal B (**2231**) (**307**). *Plagiochila fruticosa*, *P. pulcherrima*, *P. hattoriana*, and *P. yokogurensis*, in particular, each display a remarkably sharp pungent taste because of their high content of plagiochiline A (**183**) (**51**).

The Swiss and German *Plagiochila porelloides* (type I) produce compounds of the plagiochiline series as the main components. In the Swiss collection, plagiochilines A (**183**), C (**185**), D (**186**), and H (**188**) have been detected together with 3 α -acetoxycyclogermacrene (**298**). A German collection elaborated plagiochiline D (**186**) and 2,3-*seco*-aromadendrane-type sesquiterpene esters derived from plagiochiline A, and octanoic (**213**), decanoic (**214**), and 4-(Z)-decanoic (**215**) acids (**867**). *P. porelloides* is morphologically very similar to *P. asplenioides* (type I); however, plagiochilines with long-chain fatty acids have not been detected in the latter species. Compounds **213** and **215**, together with another seven esters (**216–223**), have been isolated from *P. ovalifolia* (**881**, **888**). *ent*-4 β ,10 α -Dihydroxyaromadendrane (**171**), 3 α ,14-diacetoxy-2 α -hydroxycyclogermacrene (**301**), plagiochin D (**1603**), and the plagiochilines **183**, **185**, **191**, and **211** have also been found (**84**, **579**). *P. ovalifolia* has been classified in type II

because of the presence of highly oxygenated fusicoccane-type diterpenoids, fusicoplagins A-I (**1112–1119**) (**701**). The fusicoplagins **1112–1114** are also characteristic compounds of *P. sciophila*, but this liverwort does not produce any 2,3-*seco*-aromadendranes. As an example of the plagiochiline series, *P. sciophila* elaborates acyclic and cyclic bis-bibenzylyls, e.g. perrottetin E (**1638**) or plagiochin D (**1603**), and because of this was categorized as type IV (**40**). Apart from fusicoccane-type diterpenoids, 12 β -hydroxydoladella-(3*E*,7*E*)-diene (**1094**) has been isolated also from *P. sciophila* (**326**). This is the first report of the presence of dolabellanes in the genus *Plagiochila*. The second species classified in type IV is *P. barteri*. This liverwort produces marchantins C (**1579**) and H (**1583**), along with the halimane-type diterpenoid, 1(10),14-halimadien-13 ξ -ol (**1128**) (**295**).

Bis-bibenzylyls together with 2,3-*seco*-aromadendranes are characteristic compounds of *Plagiochila fruticosa* and *P. cristata*. The isoplagiochins A-D (**1604–1607**) are macrocyclic bis-bibenzylyls isolated from *P. fruticosa* (**313**). Riccardin D (**1567**) and compounds in the plagiochiline series (**185**, **188** and **192–194**) have been isolated from the Colombian *P. cristata* (**911**). However, this species also produces the cythane- and fusicoccane-type diterpenoids **1073–1077** and **1098** and **1099** (**910**, **911**), and has been classified in type II of the *Plagiochila* species. Cyathanes and fusicoccanes are characteristic compounds also for *P. dusenii* and *P. validissima* (type V), but neither 2,3-*seco*-aromadendranes nor bis-bibenzylyls have been detected (**32**). 13-*epi*-Neoverrucosane-5 β -ol (**1056**), detected in the two above-mentioned species, has also been isolated from *P. stephensoniana* (**40**). This liverwort has been classified in chemotype VII, since besides diterpenoids it also produces bibenzylyls. 3,4'-Dimethoxybibenzyl (**1501**) and 3-methoxy-4'-hydroxybibenzyl (**1482**) have been purified (**40**). *P. spinulosa*, belonging to the same chemotype VII, is characterized by the presence of fusicoccane-type diterpenoids, bibenzylyls, and dimers derived from the two previously mentioned groups of compounds, spinuloplagins A (**1124**) and B (**1125**) (**617**). This liverwort is also known for the presence of a wide range of 9,10-dihydrophe-nanthrene derivatives (**1773–1775** and **1780–1785**) (**165**).

Bibenzylyls and bis-bibenzylyls were observed as being characteristic for the Costa Rican *P. permista* var. *integerrima* and an unidentified *Plagiochila* species with morphological affinities to *P. permista* or *P. oresitropa*. The former species produces compounds **1482** and **1501**, previously found in *P. stephensoniana*, along with a prenylated bibenzyl, **1525**, and a bibenzyl with a 2,2-dimethylchromene-ring skeleton, **1507** (**33**). Compound **1525** has also been isolated from *P. ovalifolia* (**701**) and the structurally similar compound, **1527**, occurs in *P. satoi* (**617**). There are only three examples of the presence of prenylated bibenzylyls in *Plagiochila* species. This is quite interesting chemically since such compounds are chemical markers of *Radula* species, as was stated in Sect. 8.3.6.3. Apart from bibenzylyls and bis-bibenzylyls, isoplagiochins A (**1604**), E (**1608**), F (**1609**), and 12-chloroisoplagiochin D (**1612**), together with the 9,10-dihydrophenanthrenes, **1770–1776** and **1779**, have been isolated (**33**). Compounds **1482** and **1609** have also been detected in an unidentified Costa Rican *Plagiochila* species, together with the other simple bibenzylyls, **1494** and

1495, and bis-bibenzyls such as riccardin C (**1566**), isoplagiochins C (**1606**), D (**1607**), and G (**1610**), plagilin (**1635**), isoplagilin (**1636**), and plagiolin (**1637**) (**34**).

Highly oxygenated bicyclogermacranes (e.g. **303**, **304**) have been isolated from English and Scottish samples of *Plagiochila atlantica* (type I), along with plagiochiline C (**185**) (**691**). Compound **303**, 2,5-fusicoccadiene (**1095**), and plagiochilines A (**183**) and C (**185**), have been found in *P. aerea* (type II) (**334**). Chemical analysis of *P. ericicola* (type I) collected in Zaire led to the isolation of (+)-3 α -acetoxy-2 α -[3-(4-hydroxy-3-methoxyphenyl)-propanoyloxy] bicyclogermacra- (*E*)1(10),4(12)-dien-5 β -ol (**306**), together with 3 α -acetoxybicyclogermacrene (**298**) and plagiochilines C (**185**), H (**188**), and R (**195**) (**911**).

The Ecuadorian *Plagiochila longispina* (type VI) is a distinctive liverwort since it produces 1,4-dimethylazulene (**230**) and its derivatives (**753**). Compound **230** has also been found in a Costa Rican sample and in the Bolivian *P. diversifolia* (**330**). 1,4-Dimethylazulene (**230**) has been isolated from the Ecuadorian *P. micropterix* together with plagiochilines A (**183**) and B (**184**) (**570**). The former two liverworts do not produce 2,3-*seco*-aromadendranes, but they elaborate unusual partially hydrogenated bibenzyls of the longispinone and longispinol types (**1472–1474**) (**330**, **752**). These compounds have also been detected in *P. buchtiniana* (**330**). Apart from the presence of compounds **1472–1474**, *P. longispina*, *P. buchtiniana*, and *P. diversifolia* are characterized by the occurrence of phthalides. All of the species mentioned above produce 3-(4'-methoxybenzyl)-7-methoxyphthalide (**1812**). 3-(4'-Methoxybenzyl)-7-hydroxyphthalide (**1811**) has been found in *P. buchtiniana* and *P. diversifolia*, which also produce compounds **1813** and **1814** (**330**). However, *P. diversifolia* is more variable chemically than *P. longispina* and *P. buchtiniana* and two distinct chemotypes have been recognized among the samples studied. Chemotype I is characterized by the presence of 1,4-dimethylazulene (**230**) and the methoxylated phthalides, **1812–1814**, and also by the absence of the bibenzyl derivatives, **1472–1474**. Chemotype II does not produce 1,4-dimethylazulene (**230**). The occurrence of 2,5-fusicoccadiene (**1095**), the bibenzyl derivatives, **1472–1474**, acacetin (**1912**), and 3-(4'-methoxybenzyl)-7-hydroxyphthalide (**1811**) has been documented (**330**).

The Madagascan *Plagiochila terebrans* biosynthesizes trifarienol B (**907**). This rare sesquiterpenoid has been isolated previously from the Malaysian *Cheilolejeunea trifaria* (Lejeuneaceae) (**40**). Since trifaranes are biogenetically related to pinguisanes (**813**) these liverworts seem to be similar to the *Plagiochila* species classified in chemotype IX, or the pinguisane type. *P. alternans*, *P. retrospectans*, and *P. rosariensis* belong to chemotype X and, as indicated for *P. terebrans*, are chemically very different from the other *Plagiochila* species so far examined. Dehydropinguisone (**859**) and deoxopinguisone (**862**) have been detected in *P. retrospectans* and *P. alternans*. Compound **862** and pinguisenene (**867**) have been found in *P. rosariensis* (**40**). Pinguisanes are known as significant chemical markers of some species belonging to the Lejeuneaceae, Porellaceae, Aneuraceae, and Ptilidiaceae.

The Panamanian *Plagiochila moritziana*, which has been classified in chemotype II, besides plagiochilin C (**185**), produces very characteristic dimeric

spiroterpenoids containing eudesmanolide and the fusicoccane-type diterpenoids plagiospirolides A-D (**2232–2235**), and a terpenoid arising from an aromadendrane and plagiochiline C (**185**), namely, plagiospirolide E (**2236**) (**40**, **772**). Similar dimeric terpenoids have been found also in the Japanese *P. yokogurensis* (**84**). In the above-mentioned *P. moritziana*, the eudesman-12,8-olides, diplophyllin (**676**) and diplophyllolide (**678**), have also been found (**40**, **772**). The occurrence of sesquiterpene lactones in *Plagiochila* species is rare, and, apart from *P. moritziana*, two germacranolides, costunolide (**709**) and dihydrocostunolide (**711**), and one elemene-type lactone, saussurealactone (**292**), have been detected in *P. hondurensis* (type XI) together with perrottetianal A (**1354**), a sacculatane-type diterpenoid (**40**). Compound **1354** has also been found in *P. ovalifolia* (**701**), while sacculaplagin (**2237**) occurs in *P. sciophila* (**40**). Sacculatanes are characteristic compounds for simple thalloid liverworts like *Pellia*, *Makinoa*, or *Pallavicinia*. The presence of such compounds in *Plagiochila*, *Porella*, and *Trichocoleopsis* species, which are leafy liverworts, supports the unification of both types of the liverworts into one Jungermannioopsida class.

Plagiochila trabeculata, which belongs to type III, is quite isolated from the other *Plagiochila* species, because this liverwort produces gymnomitrane-type sesquiterpenoids (e.g. **240**) as the main components along with 3 α -acetoxybicyclogermacrene (**298**) and plagiochiline H (**188**) (**39**, **40**).

Plagiochila rutilans contains various monoterpenoids, which are responsible for a peppermint-like odor caused by the presence of several menthane monoterpenoids, including, most notably, pulegone (**28**), menthone (**31**), isomenthone (**32**), terpinolene (**15**), and limonene (**19**). All these monoterpenoids have been found in Bolivian and Brazilian collections, while a Costa Rican specimen produced 3,7-dimethyl-2,6-octadien-1,6-olide (**29**) as the principal monoterpene in place of pulegone (**28**) (**693**). *P. rutilans* also elaborates the hydroquinone derivatives, **1802–1805**, as prominent components, together with a small amount of 3-hydroxy-4'-methoxybibenzyl (**1483**). In contrast to *P. rutilans*, the morphologically similar Costa Rican *P. standleyi* produces a large amount of compound **1483**. This liverwort also exhibits a peppermint-like odor, but, in this case, the main components responsible are limonene (**19**), β -phellandrene (**27**) and α -terpinene (**13**), and the rare natural product, ascaridole (**39**) (**693**).

Plagiochila bispinosa, *P. durcinalis*, and *P. subobdura* have been classified in chemotype X because of the presence of cuparane- and herbertane-type sesquiterpenoids. All three species elaborate cuparene (**464**), 1-cuparenol (**482**), and 1,2-cuparenediol (**487**). 1,2-Herbertenediol (**512**) and (–)- α -formylherbertenol (**515**) additionally have been detected in *P. subobdura*, while α -herbertenol (**509**) occurs in *P. bispinosa* (**40**).

Type XII of the *Plagiochila* species is characterized by the occurrence of everninic acid methyl ester (**1736**) together with wide range of other aromatic compounds, especially 9,10-dihydrophenanthrenes. Besides a large amount of compound **1736**, *P. bifaria* produces the 9,10-dihydrophenanthrenes, **1770** and **1776**, and the methyl benzoates, **1739** and **1740** (**221**, **277**). Compounds **1739** and **1740** have been also detected in other *Plagiochila* species belonging to this

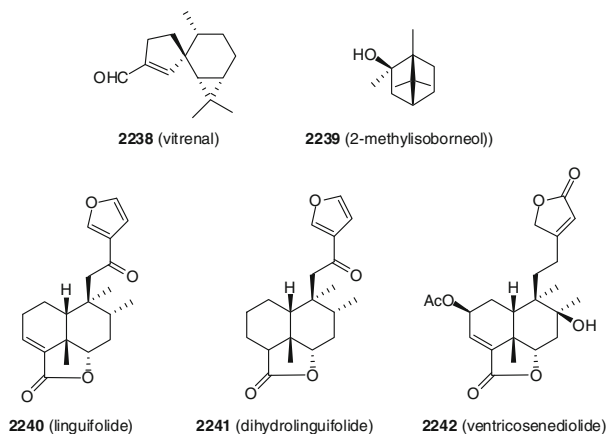
chemotype, *P. killarniensis*, *P. retrorsa*, and *P. stricta* (221, 696). All of these liverworts also biosynthesize 9,10-dihydrophenanthrenes (689, 696, 698, 699). The main components of *P. killarniensis* are methyl everminate (1736), methyl 6-methoxy-2-methyl-3,4-methylenedioxybenzoate (1739), and killarniensolide (1806) (696). 2-Hydroxy-3,5-dimethoxy-9,10-dihydrophenanthrene (1770) and 2-carbomethoxy-3,4-dihydroxy-4'-methoxybibenzyl (1480) are the most abundant constituents that have been detected in *P. retrorsa* (698). *P. stricta* produces mainly *allo*-ocimene (4) and *neo-allo*-ocimene (5), which are responsible for the characteristic smell of this liverwort, together with a large amount of 2-carbomethoxy-3,4-dihydroxy-4'-methoxybibenzyl (1480) (699). Methyl everminate (1736) and killarniensolide (1806) have been detected as the main components of *P. bifaria* from Ecuador and Tenerife, while 2-hydroxy-3,5-dimethoxy-9,10-dihydrophenanthrene (1770) was found in specimens collected in Bolivia, Brazil, and Costa Rica (333). Interestingly, one of the Brazilian specimens of *P. bifaria* produced neither methyl everminate (1736) nor 9,10-dihydrophenanthrenes. Relatively large concentration levels of 9-(4-methoxyphenyl)-6-nonen-2-one (1858) have been detected in this species (333).

Apart from the genus *Plagiochila*, the Plagiochilaceae comprises eleven other genera, among which *Plagiochilion* and *Pedinophyllum* species have been investigated chemically. *Plagiochilion conjugatus* produces *ent*-eudesma-4(15),11-dien-8 β -ol (610) together with the two eudesm-12,8-olides, 649 and 650 (72). The presence of eudesmane-type sesquiterpene lactones with a 12,8-olide moiety makes this species similar to *Plagiochila moritziana* (see above). Analysis of the ether extract of the Scottish *Pedinophyllum interruptum* led to the isolation of the prenylated benzoic acid derivatives, 1742–1745, and the 2,2-dimethyl-2*H*-chromenes, 1824–1827 (214). 2,2-Dimethyl-2*H*-chromenes are very rare among the liverworts. The only chromene derivatives that have been reported are structural variations of prenylated bibenzyls in which a prenyl side chain of the bibenzyl is cyclized to give 2,2-dimethylchromene derivatives, which have been detected in *Radula* species (see Sect. 8.3.6.3). However, 2,2-dimethylchromane derivatives do occur in *Metacalypogeia cordifolia* and *Cephalozia otaruensis* (894).

8.3.8.6 Lepidoziaceae

The Lepidoziaceae is a family of about 29 genera representing 1,000 liverworts that are found mostly in the Southern Hemisphere (341). *Lepidozia* is a large genus with about 300 species and is classified in the Lepidozioideae subfamily within the Lepidoziaceae. The *Lepidozia* species chemically studied are rich sources of sesquiterpenoids. *Lepidozia fauriana* has been chemically divided into the (1) amorphane, (2) chiloscyphane, and (3) eudesmane chemotypes (747). All of these chemotypes occur in *L. fauriana* growing in Taiwan (645, 746, 747). Chiloscyphanes (446, 453) are the main components of *L. fauriana* collected in the Malaysian part of Borneo (490). The Japanese and Taiwanese *L. vitrea* produce mainly the eudesmane-type sesquiterpenoids, 603, 605, 606, and 647 (645, 746, 871).

A previous study concerning the Japanese *L. vitrea* led to the isolation of the vitrane-type sesquiterpenoid, vitrenal (**2238**) (40). Thus, the Japanese *L. vitrea* is divided into at least two chemotypes, of which one contains vitrenal (**2238**), while the other elaborates mainly eudesmanes (871). Surprisingly, from the Japanese *L. vitrea*, the prenylated bibenzyls **1521** and **1530** have also been isolated (871), which are most important chemical markers of the Radulaceae family (see Sect. 8.3.6.3). These bibenzyls have not been found in any other Lepidoziaceae species.



A vitrane-type sesquiterpenoid found in *Lepidozia vitrea*, 2-methylisoborneol, a homomonoterpene from *Lophocolea heterophylla*, and furanoclerodane-type diterpenoids from *Demotarisia linguifolia* and *Lophozia ventricosa*

The Costa Rican *Lepidozia incurvata* produces chlorinated bis-bibenzyls of the isoplagiochin C type and bazzanins L-R (**1627–1633**) together with isoplagiochin C (**1606**) (714). These compounds are the first bibenzyls reported from the genus *Lepidozia*, but bazzanins A-K (**1616–1626**) have also been isolated from *Bazzania trilobata*, which belongs to the same family, the Lepidoziaceae (522). In addition to bis-bibenzyls, this liverwort also produces lignans. Epiphylllic acid (**1690**) and its derivatives **1697** and **1712** have been isolated (183). These types of lignans have also been found in *B. trilobata* (523, 713) and also in *Lepicolea ochroleuca* (177) and *Jamesoniella autumnalis* (809).

In the essential oil of the German *Lepidozia reptans*, barbatane, bicyclo-germacrane, cuparane, eudesmane, lepidozane, spirovetivane, and valencane sesquiterpenoids have been found, of which (+)-1(10)-spirovetiven-7 β -ol (**899**) and (–)-1(10)-valencen-7 β -ol (**572**) are characteristic chemical markers (681). The New Zealand liverwort, *L. spinosissima*, was investigated chemically to afford the cyclogorgonane-type sesquiterpenoid, 1,5-cyclo-3,6-gorgonadien-15,11-olide (**721**), together with 3 α -acetoxybicyclogermacrene (**298**), 3 α -acetoxy-*ent*-maalian-4 β -ol (**804**), and 5 β -hydroxy-*ent*-aromadendr-1-en-3-one (**174**) (72, 611). The main component of the New Zealand *L. microphylla* is a sacculatane-type diterpenoid, perrottetianal A (**1354**) (72). *L. microphylla* and *L. incurvata* are chemically quite distinct from the other *Lepidozia* species, which produce mainly sesquiterpenoids.

The genus *Kurzia*, like *Lepidozia*, also belongs to the Lepidozioideae subfamily of the Lepidoziaceae, but there seems to be no chemical relationship between *Kurzia* and *Lepidozia*. The Japanese *Kurzia makinoana* produces 5-hydroxycalamenene (**406**) as the main component together with calamenene (**403**), 7-hydroxycalamenene (**408**), and other sesquiterpenoids (**882**). Calamenenes have been found in a few *Bazzania* species, comprising *B. trilobata*, *B. tricrenata*, and *B. nitida* (**84**, **289**, **715**). The genus *Bazzania* is classified in the subfamily Bazzanioideae of the Lepidoziaceae. There are two chemotypes of *Bazzania* species, namely, the albicanyl (drimenyl)-caffeate-cuparane- (I) and the calamenane- (II) types. Thus, the above-mentioned *Bazzania* species, *B. trilobata*, *B. tricrenata*, and *B. nitida*, in which calamenenes have been detected, belong to the second chemotype (**84**, **289**, **715**). The former type I includes *B. fauriana*, *B. decrescens*, *B. japonica*, and *B. yoshinagana* (**40**, **291**, **821**).

Apart from calamenenes, *Bazzania trilobata* and *B. nitida* (type II) produce myltaylane-type sesquiterpenoids, while *B. japonica* (type I), *B. madagassa* and *B. tridens* are characterized by the presence of cyclomyltaylane-type sesquiterpenoids (**68**, **293**). It is interesting to note that cyclomyltaylane-containing *Bazzania* species do not show the presence of calamenenes (**40**, **291**, **293**). An exception to this is *B. japonica*. From a Chinese collection of this liverwort, bazzaniol A (**417**), possessing the rearranged calamenene skeleton, has been isolated (**498**). Myltaylanes and cyclomyltaylanes are very rare sesquiterpenoids found only in liverworts from the genera *Bazzania*, *Mannia*, *Mylia*, and *Reboulia*.

The Madagascan *Bazzania decrescens* is very similar chemically to *B. japonica*, although the latter contains albicanol (**539**) and albicanyl caffeate (**542**) instead of drimenol (**538**) and drimenyl acetate (**541**). The only other difference between these two species is the presence of cyclomyltaylane-type sesquiterpenoids in *B. japonica*. Morphologically, *B. decrescens* is very close to *B. madagassa*. However, neither myltaylanes nor cyclomyltaylanes have been detected in *B. decrescens* (**291**).

Japanese and Taiwanese specimens of *B. tridens*, besides cyclomyltaylane (**819**), present in all investigated samples, were found to produce aromadendrane sesquiterpenoids. Tridensenone (**155**) and/or cyclocolorenone (**126**) have been found as the main components (**40**, **846**, **951**). It is noteworthy that in the Japanese *B. tridens*, an additional monocyclofarnesane-type sesquiterpenoid, tridensenal (**811**), has been detected, while the Taiwanese specimen additionally produces aristolanes, acoranes, and bisabolanes (**846**, **951**, **959**).

The most characteristic chemical constituents of *Bazzania trilobata* are the chlorinated macrocyclic bis-bibenzyl derivatives, the bazzanins (**1616**–**1625**, and **1634**) and the phenanthrene-bibenzyl derivative, **1626** (**522**, **713**). As mentioned above, bazzanins have also been found in the Costa Rican *Lepidozia incurvata* (**714**). These are the only two examples of the presence of such compounds in the family Lepidoziaceae, but, however, chlorinated bis-bibenzyls have been isolated from *Mastigophora* and *Herbertus* species (**321**) (see Sects. **8.3.8.2** and **8.3.8.3**).

Bazzania harpago, *B. spiralis*, and *B. praerupta*, collected in the Malaysian part of Borneo, are not closely related chemically to one another. Barbatanes are characteristic of *B. harpago*, eudesmanes of *B. spiralis*, and drimanes of

B. praerupta (490). The New Zealand *B. novae-zelandiae* is chemically very characteristic since it produces the pinguisane-type sesquiterpenoid naviculol (845) and its caffeate (846) (145). Pinguisanes are characteristic compounds of *Lejeunea*, *Porella*, *Ptilidium*, and *Trichocolea*. This is the first report of the presence of pinguisanes in the genus *Bazzania*.

8.3.8.7 Lophocoleaceae

Within the family Lophocoleaceae, five genera have been studied chemically. These are *Chiloscyphus*, *Clasmatocolea*, *Heteroscyphus*, *Leptoscyphus*, and *Lophocolea*. The Japanese *Chiloscyphus polyanthos* elaborates the eudesmane and chiloscyphane sesquiterpenoids, 603, 605, 609, and 613, and 444 and 445, respectively (890). It is interesting to note that eudesm-3-en-7 α -ol (603) is enantiomeric to a compound found in *Lepidozia vitrea*, while eudesm-4(15)-en-7 α -ol (605) occurs in both species as a mixture of enantiomeric isomers (56:44 area % for *C. polyanthos* and 72:28 for *L. vitrea*) (890). From a Chinese collection of *C. polyanthos*, rearranged calamenanes (414–416) have been isolated (498), while French and English specimens produce intensely pungent *ent*-12,8-eudesmanolides like diplophyllin (676) or diplophyllolide (678) (55). The European *C. polyanthos* is closely related chemically to the Colombian *Clasmatocolea vermicularis*, since this species also produces diplophyllin (676) (55). *ent*-12,8-Eudesmanolides have also been isolated from *Diplophyllum* and *Scapania* species belonging to the Scapaniaceae family (15, 569). The Japanese *C. polyanthos* does not contain eudesmanolides and is chemically rather similar to the Taiwanese *C. pallescens*, since it elaborates chiloscyphane-type sesquiterpenoids together with oppositanes (40). Chiloscyphanes and oppositanes have also been found in the American *C. rivularis* (956). These compounds seem to be good chemical markers for these two *Chiloscyphus* species. The chiloscyphanes have also been found in *Lepidozia fauriana* and in *Jungermannia vulcanicola* (585, 645), while a very similar *ent*-oppositane-type brominated sesquiterpene alcohol (2280) has been isolated from the red alga, *Laurencia subopposita* (284).

C. subporosus from New Zealand produces mainly aromadendranes 136 and 176 and eudesmanes as well as the very characteristic aromadendrane-guaianolide-type sesquiterpene dimer, 177, which seems to be a good chemical marker for this species (606). The New Zealand *C. pallidus* emits a very strong stinkbug-like smell. The odorous components are the simple aliphatic aldehydes, 1942–1945, and, among them, (*E*)-dec-2-enal (1944) is the major compound (72). *C. pallidus* is chemically quite distinct from any other liverworts so far examined since it produces neither terpenoids nor aromatic compounds.

The French *Lophocolea heterophylla* is chemically very unusual since it produces the homo-monoterpene, 2-methylisoborneol (2239), which is responsible for the characteristic fragrance of this liverwort. This liverwort elaborates also calamenanes and eudesmane-type sesquiterpene lactones (864). From a German specimen, furanoeudesma-4(15),7,11-trien-5 α -ol (626) has been isolated (678). The presence of eudesmanes and 12,8-eudesmanolides in *L. heterophylla* make

this liverwort similar chemically to *C. polyanthos* (see above). The very characteristic epoxy-trinoreudesmane sesquiterpene, **925**, has been isolated from *L. bidentata* collected in Germany (679).

Aromadendrane-type sesquiterpenoids and clerodane-type diterpenoids seem to be good chemical markers for *Heteroscyphus* species. These classes of compounds have been detected in *H. aselliformis*, *H. coalitus*, and *H. planus* (40, 310, 488, 489, 873). Clerodanes have also been found in *H. billardieri* (607, 635).

Clerodane-type diterpenoids isolated from *Heteroscyphus planus* are very characteristic since they possess a spiro structure (956–959) (310). Nabeta and associates reported the isolation of the clerodane-type carboxylic acids, **961–963**, from *in vitro* cultures of *H. planus* (561), which might be precursors of the spiroclerodanes. However, these diterpene acids have not been found in any field-collected species. In addition to clerodanes, *H. planus* also elaborates the *ent*-2,3-*seco*-aromadendrane-type sesquiterpenoids, **182**, **183**, **190**, and **210**, and the isoplagiochin-type macrocyclic bis-bibenzyls, **1602** and **1604**, which are significant chemical markers of the Plagiochilaceae (310, 563, 564).

Apart from aromadendranes and clerodanes, *Heteroscyphus coalitus* produces the halimane-type diterpenoids, **1130** and **1131** (873). Halimanes are very rare in Nature and besides the liverworts mentioned have been found in *Jungermannia hyalina* and *J. infusca* as well as *Plagiochila barteri* (295, 580, 598).

Leptoscyphus jackii produces *ent*-1 α -hydroxy-3-maaliene (**801**) as the major component. This compound might be a valuable chemical marker for *Leptoscyphus*, since maalianes have not been found in any other liverworts belonging to the Lophocoleaceae family (893).

8.3.8.8 Lepicoleaceae

The Lepicoleaceae has been considered a rather primitive family among the Marchantiophyta, and from a morphological point of view is closely related to the families Ptilidiaceae and Mastigophoraceae (722). However, there is no chemical relationship between these taxa.

The Colombian species, *Lepicolea pruinosa*, produces two eudesmane-type sesquiterpene lactones, frullanolide (**658**) and dihydrofrullanolide (**660**), as the major constituents, in addition to several other known sesquiterpenoids (39). The Chilean *L. ochroleuca* elaborates sesquiterpenoids with an aromadendrane skeleton and diterpenoids of the neoverrucosane and fusicoccane types, although no eudesmanolides have been detected (478). This liverwort also produces 2,4,6-trihydroxyacetophenone-3,5-di-*C*-glucoside (**1724**), protocatechuic acid 4-*O*- β -glucoside (**1869**), and the lignans, **1692–1695** (177). Compound **1724** has been isolated previously from *Adelanthus lindenbergianus* (116). Lignans have been also detected in *Bazzania*, *Chiloscyphus*, and *Lophocolea* species, which like the *Lepicolea* genus, have been classified in the Lophocoleineae suborder of the Jungermanniales (see Sects. 8.3.8.6 and 8.3.8.7).

8.3.8.9 Pseudolepicoleaceae

Blepharostoma trichophyllum, which belongs to the Pseudolepicoleaceae family, is a rich source of the labdane-type diterpenoids, **1283–1287** (215). This liverwort also produces blepharostol (**551**), possessing a rearranged drimane skeleton, which seems to be a good chemical marker for this species. It is noteworthy that blepharostol caffeate (**552**) has been isolated from *Bazzania novae-zelandiae* (899). Similar rearranged drimane-type sesquiterpenoids have also been reported from the marine sponge *Disidea avara* (546).

8.3.8.10 Adelanthaceae

The Adelanthaceae comprises four genera, among which *Adelanthus* and *Wettsteinia* have been investigated chemically. *Wettsteinia* species are chemically quite different from the other liverworts so far examined because of the presence of simple naphthalene and isocoumarin derivatives. In the Taiwanese *W. inversa*, isocoumarins, inversin (**1660**), dihydroinversin (**1661**), and 8-hydroxy-6,7-dimethoxy-3-methylisocoumarin (**1663**), together with wettstein C (**1681**), have been detected (407). Compounds **1661** and **1681**, along with another isocoumarin (**1662**) and the naphthalenes **1679** and **1680**, have been isolated from the New Zealand *W. schusterana* (69). A difference between these two *Wettsteinia* species is the presence of isocoumarin and naphthalene derivatives with a tetrasubstituted benzene ring in *W. schusterana*.

Adelanthus decipiens is very similar chemically to *Wettsteinia* species. Analysis of *A. decipiens* from Scotland, Wales, Ireland, Colombia, and Ecuador led to the detection of the naphthalene derivatives, **1679–1681**, **1683**, and **1684**. In contrast to *Wettsteinia* species, *A. decipiens* elaborates the acetophenone derivatives, **1718–1721**, and **1723** (695). Acetophenones **1724** and **1725** have also been found in the Patagonian *A. lindenbergianus*; however, the major constituents of this liverwort are the clerodane-type diterpenoids, **977–984** (116). Clerodanes have not been detected in *A. decipiens*.

8.3.8.11 Cephaloziaceae

Up to the present time, only one *Cephalozia* species, *C. otaruensis*, has been investigated chemically. This liverwort produces 6-hydroxy-5-methoxy-2,2-dimethyl-7-(3-methyl-2-butenyl)-chroman (**1818**). This compound, together with other chromane derivatives, has been isolated from *Metacalypogeia cordifolia* (Calypogeiaceae) (894) (see Sect. 8.3.8.18). Thus, both liverworts are closely related chemically, even though they are different morphologically.

The Cephaloziaceae also includes the genus *Odontoschisma*. *O. denudatum* produces a large amount of the aromadendrane sesquiterpene, anastreptene (**122**),

which is widely distributed in liverworts. The most characteristic chemical feature of *O. denudatum* is the presence of the dolabellane-type diterpenoids, **1085–1093**, along with the *ent*-vibsanes, **1404–1408**, and neodenudatenones, **1409** and **1410** (**316**, **317**, **319**, **326**). Thus, chemically, *O. denudatum* is very different from any other liverwort since *ent*-vibsanes and neodenudatenones have not been detected in or isolated from any other plants. Dolabellane-type diterpenoids are widespread in marine algae and also have been reported from the liverworts, *Barbilophozia* species, *Chandonanthus hirtellus*, and *Plagiochila sciophila* (**40**, **326**, **583**, **927**).

8.3.8.12 Jamesoniellaceae

In the new classification of the Marchantiophyta, the genus *Jamesoniella* was excluded from the Lophoziaceae family and placed into the independent Jamesoniellaceae family together with another eight genera (**168**, **169**).

The chemical constituents of *Jamesoniella autumnalis* are very complex. This species elaborates kaurane, labdane, and clerodane diterpenoids, among which the furanoclerodanes (e.g. **1005–1010**) might be responsible for the bitter taste of this liverwort (**40**, **808**, **809**, **811**). Clerodanes **1013** and **1014** and furanoclerodane **1011** together with labdane-type diterpenoids have also been detected in *J. colorata*. Besides the diterpenoid constituents of this liverwort, the sesquiterpene, waitziacuminone (**933**), and the chlorinated bis-bibenzyl, 6,10,12,6',10',12'-hexachloroisoperrottetin A (**1643**), have also been isolated (**340**).

Labdanes and clerodanes have not been detected to date in two further *Jamesoniella* species, *J. tasmanica* and *J. kirkii*. The former species produces mainly kaurane and cyathane diterpenoids (**870**) and the latter kauranes and isopimaranes (**612**). Cyathanes found in *J. tasmanica* belong to the 13-*epi*-neoverrucosane and 13-*epi*-neohomoverrucosane types (**872**). 13-*epi*-Neoverrucosanes have also been found in *Heteroscyphus planus*, *Schistochila nobilis*, and *Plagiochila stephensoniana* (**40**, **310**), but, up to now, 13-*epi*-neohomoverrucosanes have been isolated only from *J. tasmanica*, and seem to be good chemical markers for this liverwort.

A 13-*epi*-pimarane-type diterpene acid, 13-*epi*-pimara-9,15-dien-20-oic acid (**1324**), is the main metabolite of *Cuspidatula momodon* (**72**), which like *Jamesoniella* species, is classified in the family Jamesoniellaceae. *ent*-16-Kaurene (**1133**), along with a few common sesquiterpenoids, has also been detected in this liverwort (**72**). The presence of pimarane- and kaurane-type diterpenoids makes this liverwort similar to *Jamesoniella kirkii* (see above).

The genus *Demotarisia*, previously classified in the family Jungermanniaceae, resembles morphologically the genus *Jamesoniella*. *D. linguifolia* elaborates a furanoclerodane diterpenoid, linguifolide (**2240**), and its 3,4-dehydro derivative (**2241**) as the major components (**40**). Furanoclerodanes, as mentioned above, have been found in *Jamesoniella autumnalis* and *J. colorata*.

8.3.8.13 Scapaniaceae

The new classification of the liverworts proposed by *Crandall-Stotler et al.* (168, 169) united the Lophoziaceae, Scapaniaceae, and Chaetophyllopsidaceae into one family, Scapaniaceae. The chemical constituents of a few species of this new family, Scapaniaceae, are very complex and the compounds are similar structurally to those found in marine organisms.

Anastrepta orcadensis is characterized by a very bitter taste, which might be due to the presence of the clerodane-type furanoditerpenoids, anastreptin (973) and orcadensin (974). The fusicoccane-type diterpenoid, anadensin (1105), has also been isolated (358, 360).

The genus *Anastrophyllum* is characterized by the presence of spenolobane diterpenoids (1376–1387). These compounds have been detected in *A. auritum*, *A. donnianum*, and *A. minutum* as the main components (40, 139, 976). Apart from spenolobanes, the Ecuadorian *A. auritum* biosynthesizes fusicoccane and kaurane diterpenoids (976).

Dolabellane-type diterpenoids are characteristic compounds of the genus *Barbilophozia*. *B. barbata*, *B. floerkei*, and *B. lycopodioides* additionally produce fusicoccane diterpenoids. Barbifusicoccins A (1103) and B (1104) have been isolated from *B. barbata* and *B. floerkei* (40, 596). Compound 1103 has been found also in *B. lycopodioides* (583). *B. barbata* and *B. hatcheri* produce the very characteristic daucane-type sesquiterpenoid, hercynolactone (536) (593, 596). A diterpene possessing a new skeleton, hatcherenone (1419), has been found in *B. hatcheri* (593), which seems to be a good chemical marker for this liverwort. *B. hatcheri* and also *B. barbata* produce the acorane sesquiterpenoid, barbiacoriadienone (74) (593, 596). Apart from the dolabellanes and fusicoccanes, *B. floerkei* accumulates the germacrane-type sesquiterpene alcohol, (1*S*,7*R*)-germacra-4(15),5,10(14)-trien-1-ol (696). The sign of the optical rotation of this compound is in agreement with that of the same compound isolated from a brown alga; however, the antipode of this compound has been isolated from *Jackiella javanica* (570, 583).

The genus *Chandonanthus* is known for the presence of cembrane-type diterpenoids, which are chemical markers of this liverwort (45). Cembranes have been detected in and/or isolated from Tahitian, East Malaysian, Taiwanese, and Chinese samples of *Chandonanthus hirtellus* (422, 494, 748, 927, 423, 490). Interestingly, the Tahitian specimen produced *ent*-verticillol (1392) and *ent*-12-*epi*-verticillol (1393) (422, 423, 494). Verticillanes are very rare in Nature, and *ent*-verticillanes have been found only in the liverworts, *Jackiella javanica* (Jackiellaceae) (614) and in an unidentified Tahitian *Jungermannia* species (Jungermanniaceae) (494). The verticillane and cembrane diterpene skeletons can be considered as being biogenetically related and both may have a common biogenetic precursor (105, 387).

Chandonanthus hirtellus is also known for the presence of dolabellane and fusicoccane diterpenoids. Interestingly, the former class of compounds has been

found in a West Malaysian liverwort (927), with the latter in a liverwort collected in Borneo (East Malaysia) (490). Fusicocanes have also been detected in the Tahitian *C. hirtellus* (422, 423, 494). Also in the Tahitian *C. hirtellus* specimen, the presence of the acetogenins dictyotene (1936) and (*E*)-ectocarpene (1937), previously reported in brown algae (383), has been confirmed. Recently, dictyotene (1936) and the two other acetogenins, 1938 and 1939, were detected in the Greek *Fossombronina angulosa* (492) (see Sect. 8.3.2.2). It is also worth noting that cembranes, which are chemical markers of this liverwort, are also widespread in brown algae (430, 947). Such chemical similarities suggest that some families of liverworts and algae may have an evolutionary relationship.

Chemical analysis of the *C. hirtellus* subsp. *giganteus* showed the presence of the biflavone dicranolomin (2',6''-bisluteolin) (1909) (441), a compound first detected in the moss *Dicranoloma robustum* (250). This is the first report of the presence of biflavonoids in this liverwort.

Gymnocolea inflata produces bitter-tasting compounds. Gymnocolin (976), a clerodane-type diterpenoid, is one of the bitter principles and an important chemical marker of this species (40, 882). The clerodane-type diterpenoid, ventricose-nediolide (2242), has been found in *Lophozia ventricosa*, together with eudesmane-type sesquiterpenoids (486, 839).

Diplophyllum is another genus of the family Scapaniaceae. Chemical analysis of *D. taxifolium* and *D. albicans* indicated the presence of *ent*-eudesmane-type sesquiterpenoids together with the eudesmane-type sesquiterpene lactone, diplophyllin (676), which is the main component of both species (39). In addition to compound 676, *D. albicans* produces *ent*-dihydrodiplophyllin (677) and *ent*-diplophyllolide (678) (15). Diplophyllin (676) and other sesquiterpene lactones have not been detected in *D. serrulatum*, and this liverwort produces drimane-type sesquiterpenoids (868). Hence, *D. serrulatum* is chemically distinct from *D. taxifolium* and *D. albicans*. There is also no chemical affinity between the above-mentioned *Diplophyllum* species and *D. plicatum*, since the latter species produces the furanoclerodanes 15,16-epoxy-*cis*-cleroda-3,13(16),14-trien-18-oic acid (1053) and 15,16-epoxy-*cis*-cleroda-13(16),14-dien-18 α ,6 α -olide (1054) (84).

Tritomaria polita is closely related chemically to *T. quinquedentata* since both produce eudesmane-type sesquiterpenoids. However, *T. quinquedentata* elaborates the sesquiterpene lactone, *ent*-diplophyllolide (678) as the major component, while the former species does not (18, 928). Eudesmanes have also been detected in *Lophozia ventricosa*, which makes this liverwort similar to species in the *Tritomaria* genus, especially to *T. polita*, since both produce (+)-eudesma-3,7 (11)-dien-8-one (629) (18, 486).

The genus *Scapania*, with 82 species, is the largest group of the Scapaniaceae family and shows a high diversity of morphotypes (662). *Scapania* species are also characterized by high chemical diversity. *Scapania undulata* is highly evolved by chemical criteria since the features of its sesquiterpenoids are very complex (40). There are three chemotypes of *S. undulata*: the muurolane- and cadinane-type (I), the longibornane-type (II), and the labdane-type (III). The Belgian *S. undulata* produces muurolanes and cadinanes, (+)-1-*epi*-cubenol (358), *ent*-T-muurolol

(396), scapanol (398), (+)-4-muurolen-6 α -ol (399), and 1,4-peroxy-5-muurolene (400), as the main components (577, 569). A German specimen was found to elaborate mainly (–)-longiborneol (781) and also longifolene (778) and the longipinane derivatives, 782–784, and belongs to the second chemotype (16). Compounds 781 and 784 have also been found in a Japanese specimen; however, the main compounds from this liverwort are labdane-type diterpenoids. Since labdanes (1290–1292) and dimeric labdanes (1293 and 1294) are the most characteristic compounds of this specimen, and it was classified as a member of the third chemotype of *S. undulata* (973). Labdanes have also been detected in German and Scottish *S. undulata* (40).

Aromadendrane- and longifolene-type sesquiterpenoids and also *seco*-clerodane- and *cis*-clerodane-type diterpenoids have been found in *Scapania nemorea* (253, 569). Interestingly, in the German *S. nemorea*, *ent*-diplophyllin (676) has been detected (569). This is the first report of the 12,8-eudesmanolides in *Scapania* species, although this class of eudesmane lactones is characteristic for *Diplophyllum* species belonging to the same family. The clerodane-type diterpenoids, parvitexins A-E (998–1002), have been found in the Japanese *S. parvixeta* (393). Subulatin (1864), a caffeic acid derivative, has also been isolated from this species (823). Like *S. nemorea* and *S. parvixeta*, *S. bolanderi* also produces clerodane diterpenoids. From this Japanese specimen, 2 β -acetoxy-18-carboxymethylcleroda-3,13-dien-15-oic acid (1029) has been isolated (818). Besides clerodanes, this species synthesizes verrucosane- and neoverrucosane-type diterpenoids (527). The occurrence of the cyathanes is very rare in Nature; they were isolated first from *Mylia verrucosa* and also detected in some *Fossombronina*, *Schistochila*, *Plagiochila*, and *Heteroscyphus* species (39, 45). The isolation of cyathanes from *Scapania bolanderi* is only one example of the presence of such a class of diterpenoids in *Scapania* species and the Scapaniaceae family. These compounds seem to be good chemical markers for this *S. bolanderi*.

Other *Scapania* species investigated chemically, e.g. *S. aequiloba*, *S. ampliata*, *S. ornithopodioides*, *S. reflexa*, *S. robusta*, and *S. verrucosa*, produce mainly sesquiterpenoids, which are common in other liverworts. The most common sesquiterpenes are anastreptene (122) and aromadendrene (156) (39, 40, 273).

8.3.8.14 Acrobolbaceae

Among seven genera classified in the family Acrobolbaceae, only three have been chemically investigated; these are *Lethocolea*, *Marsupidium*, and *Tylimanthus*.

Lethocolea glossophylla from Ecuador produces the prenylated bibenzyls, 1536–1539, as the main components, and a prenyl bis-bibenzyl, glossophyllin (1563) (447). Bibenzyls have also been found in *Marsupidium* species. *M. perpusillum* elaborates simple bibenzyls such as 3-hydroxybibenzyl (1492), 3-methoxybibenzyl (1493), 3-methoxy-4'-hydroxybibenzyl (1482), and its dehydro derivative (1484) (72). *M. epiphytum* is more evolved chemically than the former species, since it produces bibenzyls possessing the dihydrooxepin skeleton (1517 and 1518) and prenylated bibenzyls (1547–1549) (635). Bibenzyls with a

2,2-dimethylchromene ring skeleton (**1507** and **1508**) have been found in the New Zealand *Tylimanthus saccatus* (72). On the other hand, the Chilean *T. urvileanus* produces dihydrobenzofuran derivatives like tylimanthin B (**1506**) (40). Bibenzyl derivatives might be significant chemical markers of the family Acrobolbaceae, although this class of compounds has been isolated from *Radula* species (Radulaceae) (see Sect. 8.3.6.3), and also from some *Frullania* (Frullaniaceae) (see Sect. 8.3.6.4) and *Plagiochila* species (Plagiochilaceae) (see Sect. 8.3.8.5).

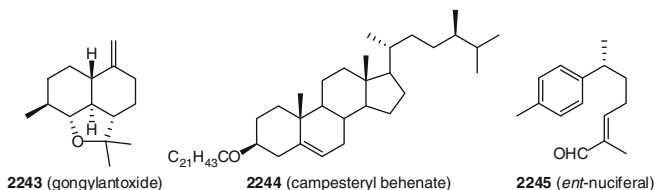
However, there are some exceptions among *Tylimanthus* species. The New Zealand *T. tenellus* produces unprecedented sesquiterpene esters with an aromatic γ -lactone acid moiety (**772** and **773**), together with sesquiterpenoids (**575**, **577**, and **771**), with pulvinic acid methyl ester (**1866**) as the main component (896). From the Argentine *T. renifolius*, herbertane, aromadendrane sesquiterpenoids (**173**, **509**, **510**, and **514**), diterpenoids (**1321** and **1345**), and several flavones and flavanones (**1922–1926** and **1928–1932**), have been isolated (213). In both of these species, bibenzyls have not been detected to date.

8.3.8.15 Antheliaceae

The genus *Anthelia* is the only member of family Antheliaceae within the order Jungermanniales. The Russian liverwort *Anthelia julacea* produces *ent*-16 β -hydroxykaurane (**1154**) as its major component, together with bisabolane-type sesquiterpenoids (574). Compound **1154** has also been found in *A. juratzkana* (39). Therefore, this *ent*-kaurane-type diterpenoid might be a useful chemical marker for the Antheliaceae.

8.3.8.16 Arnelliaceae

The Arnelliaceae family includes the genera *Arnellia*, *Gongylanthus*, *Southbya*, *Stephaniella*, and *Stephaniellidium*, of which *Gongylanthus ericetorum* has been investigated chemically. Gongylantoxide (**2243**), a cadinane sesquiterpene ether, is a chemical marker for this species (40). It is noteworthy that a similar compound, veticadinoxide (**2166**), has been isolated from the essential oil of the hornwort, *Anthoceros caucasicus* (540).



Gongylantoxide, a cadinane-type sesquiterpenoid found in *Gongylanthus ericetorum*, campesteryl behenate from *Calypogeia* species, and *ent*-nuciferal from *Anthelia julacea*

8.3.8.17 Balantiopsidaceae

The Balantiopsidaceae family comprises eight genera, of which *Balantiopsis* and *Isotachis* have been studied chemically. All of the *Balantiopsis* species investigated, *B. cancellata*, *B. erinacea*, and *B. rosea*, produce benzyl benzoate (1829), β -phenethyl benzoate (1830), and β -phenethyl (*E*)-cinnamate (1835) (40, 45, 457). *B. cancellata* and *B. rosea* are also known for the presence of thioacrylates. The former species produces isotachin B (1881), while from the latter, isotachins A-C (1880, 1881, and 1881a) have been found (40, 457). Besides benzoates and phenethyl alcohol derivatives in *B. rosea*, the phthalide, 1808, the prebibenzyls, 1472–1474, and their dimeric compounds (1561 and 1562), have been found (59, 84, 612). Interestingly, in two different collections of the New Zealand *B. rosea*, different compounds are evident. One specimen produces benzoates, phenethyl alcohol derivatives, thioacrylates, and a phthalide (59). Chemical analysis of the second specimen resulted in the isolation of prebibenzyls and their dimeric compounds; however, neither benzoates nor thioacrylates have been found (84, 612). Thus, there are at least two chemotypes of this species in New Zealand.

As in the case of the *Balantiopsis* species, the chemical markers of the genus *Isotachis* are benzoates and cinnamates (e.g. 1829, 1833) and phenethyl alcohol derivatives (e.g. 1828, 1835). Chemosystematic investigations of the genus *Isotachis* have shown that *Isotachis* may be divided into three groups; type I – including species containing isotachins A-C (1880, 1881, and 1881a), without the presence of terpenoids (*I. japonica*), type II – species containing sesquiterpenoids (*I. humectata*, *I. divergens*, *I. lyallii*), and type III – species containing both isotachins and sesquiterpenoids (*I. aubertii*) (288). All of these chemotypes are characterized by the presence of compounds that are chemical markers of this genus.

8.3.8.18 Calypogeiaceae

Some *Calypogeia* species (Fig. 8.4) contain characteristic blue oil bodies, which indicate clearly the presence of azulenes in the live plants. 1,4-Dimethylazulene (230) and other azulenoids together with aromadendrane sesquiterpenoids have been found in *C. azurea*, *C. granulata*, and *C. muelleriana* (39, 40, 816, 933). Aromadendranes, such as 1,2-dehydro-3-oxo- β -gurjunene (125), isolated from *C. azurea*, may be related biogenetically to azulenes (816). The presence of azulenoids in *Calypogeia* species is very characteristic and they seem to be good chemical markers. This class of compound has also been found in some *Barbilophozia*, *Macrolejeunea*, and *Plagiochila* species (15, 40, 330). However, Calypogeiaceae, Lejeuneaceae, Plagiochilaceae, and Scapaniaceae cannot be considered related morphologically.



Fig. 8.4 *Calypogeia tosaana*. (Permission for the use of this figure has been obtained from Mr. Masana Izawa, Saitama, Japan)

Calypogeia azurea, *C. integristipula*, *C. muelleriana*, *C. neesiana*, and *C. sphagnicola* produce campesteryl behenate (**2244**) (39, 112, 356). The presence of this sterol ester suggests that it is also a characteristic feature of this liverwort genus.

There are two *Calypogeia* species, *C. suecica* and *C. fissa* in which up to the present time azulenoids and campesteryl behenate (**2244**) have not been detected. *C. suecica* produces compounds with the bisabolane skeleton, among which (+)-bisabola-2,10-diene(1,9)-oxide (**332**) is the predominant component (934). The essential oil of *C. fissa* is dominated by the acorane-type sesquiterpenoids **68**, **73**, and **80–83** (931).

Chroman derivatives are chemical markers of the genus *Metacalypogeia*. The Japanese *M. cordifolia* produces the chroman compounds, **1818–1822**, together with sesquiterpenoids, which are very common in the liverworts (894). The sesquiterpene β -barbatene (**235**) and the dihydroisochromene, metacalypogin (**1823**) are the major constituents of the Taiwanese *M. alternifolia* and *M. cordifolia* (748). From the *Metacalypogeia* species mentioned above, no azulene components have been detected. Thus, chemically, *Calypogeia* and *Metacalypogeia* are very distinct.

8.3.8.19 Geocalycaceae

The Geocalycaceae comprises four genera, but only *Saccogyna* has been investigated chemically. The essential oil of *Saccogyna viticulosa* has been described as the sole source of zierene (**225**) and saccogynol (**227**) (164). Reinvestigation of this species confirmed the presence of these two compounds as the main

components, and showed the presence in addition of isogermacrene A (693), and gorgonane- (717–720) and aromadendrane-type (122, 160, 168) sesquiterpenoids (276). Zierane-type sesquiterpenoids seem to be good chemical markers for this liverwort. Up to the present, zieranes have also been detected as minor components in *Chandonanthus hirtellus* and some *Plagiochila* species (221, 422, 423). The occurrence of isogermacrene A (693) in this liverwort is important from the biogenetic point of view. This compound is proposed as a missing link between farnesyl diphosphate and the gorgonanes and zieranes (276). Interestingly enough, this liverwort produces viticulol (1415), a prenylguaiane-type diterpenoid (276). This was the first report of the presence of prenylguaianes in liverworts. Such compounds are mainly found in brown algae of the genera *Aplysia*, *Cystoseira*, and *Dictyota* (87, 128).

8.3.3.20 Gymnomitriaceae

Gymnomitrium obtusum is a rich source of sesquiterpenoids based on the barbatane (gymnomitrane) skeleton. Analysis of the essential oil of a German specimen led to the identification of α -barbatene (234), β -barbatene (235), gymnomitrone (239), gymnomitrol (240), gymnomitrol acetate (241), and isogymnomitrol (242), together with isobazzanene (260) and cuparene (464) (929). The Russian *G. concinnatun* was found to be chemically different from *G. obtusum*. From this species, the bisabolane aldehyde, *ent*-nuciferal (2245), and *ent*-2-hydroxycuparene (483) have been isolated (573). It is noteworthy that *ent*-nuciferal (2245) and *ent*-2-hydroxycuparene (483) also occur in the Russian *Anthelia julacea* (Antheliaceae), together with *ent*-kaurane alcohol (574).

Longipinane-type sesquiterpenoids have been found as the major and most characteristic components of the German and Russian *Marsupella emarginata*. However, the German specimen produces highly acetylated longipinanes, which have not been detected in the Russian specimen (573). A different German collection of *M. emarginata* produced longipinanes (785–790) together with barbatane-type sesquiterpenoids (e.g. 251–256) (17). Longipinanes were the main constituents of *M. aquatica* collected in France (575) while an Austrian specimen produced principally amorphane-type sesquiterpenoids (e.g. 370–372) (17, 19). Chemical analysis of the Scottish *M. emarginata* var. *aquatica* has shown the presence of amorphanes (373–376) as the major components, with no longipinanes nor gymnomitranes found (465). Longipinane-type sesquiterpenoids are also absent in the Japanese *M. emarginata* var. *patens*. From this liverwort, gymnomitranes have been isolated instead (528). Thus, this species is closely related chemically to *Gymnomitrium obtusum*, as mentioned earlier.

The chemical profile of *M. alpina* is very different from other *Marsupella* species since it produces the eudesmane sesquiterpenoids, 575, 587, 588, 590, 677, and 678, with *ent*-diplophyllolide (678) being the main compound (17). The presence of compounds 677 and 678 in *M. alpina* makes this liverwort similar

chemically to *Diplophyllum albicans*, belonging to the Scapaniaceae (see Sect. 8.3.8.13).

8.3.8.21 Jackiellaceae

The genus *Jackiella* is the only member of the family Jackiellaceae within the order Jungermanniales. *Jackiella javanica* has been investigated chemically, and is characterized by the presence of a wide range of *ent*-verticillane-type diterpenoids (1391–1403) as major components (587, 608, 614). Verticillanes are very rare in Nature. They are considered as putative biosynthetic precursors of the taxanes (418). While these compounds are also related biogenetically to the cembranes (105, 387), up to now no cembranoids have been detected in *J. javanica*. Cembranoids together with *ent*-verticillol (1392) and *ent*-12-*epi*-verticillol (1393) have been found in the Tahitian *Chandonanthus hirtellus* (423, 494).

Besides verticillane-type diterpenoids, *J. javanica* is also known for the presence of *ent*-kaurane diterpenoids and sesquiterpenoids. *ent*-Globulol (139), *ent*-4 β ,10 α -dihydroxyaromadendrane (171), *ent*-cubeban-11-ol (463), *ent*-4(15)-eudesmene-1 β ,6 α -diol (622), *ent*-15 α -hydroxy-16-kaurene (1148), and *ent*-11 α -hydroxy-16-kauren-15-one (1158), have been isolated, among others (608, 614).

8.3.8.22 Jungermanniaceae

Jungermannia is one of the prominent genera of the family Jungermanniaceae, with about 125 species distributed worldwide (914). *Jungermannia* species are rich sources of clerodane-, kaurane-, and labdane-type diterpenoids. *Jungermannia infusca* is polymorphic and a taxonomically very complex liverwort. This liverwort is also chemically very diverse. There are at least four chemotypes of *J. infusca* in which the stated classes of compounds predominate, the: (I) kaurane type, (II) labdane and clerodane type, (III) bis-bibenzyl type, and (IV) cuparane and labdane type (45, 599). All of the chemotypes mentioned have been found in Japanese collections of *J. infusca* (584, 587, 591, 597, 599, 600). A Chinese specimen has been classified in the bis-bibenzyl type (III), since it contains marchantin C (1579) and riccardin C (1566) as major components (952).

The classification of *J. infusca* can also be adapted, after slight modification to the other chemically analyzed *Jungermannia* species. On the basis of chemical composition, all *Jungermannia* species, can be divided into five chemotypes, the: I – kaurane, II – labdane, III – clerodane, IV – bis-bibenzyl, and V – cuparane-labdane types.

The kaurane type I is represented by *J. atrobrunnea*, *J. exsertifolia* subsp. *cordifolia*, *J. rotundata*, *J. subulata*, and unidentified *Jungermannia* species collected in New Zealand. The Chinese *J. atrobrunnea*, apart from the *ent*-kauranes 1222–1228, produces the very characteristic rearranged *ent*-kauranes, 1219–1221 (668). The structurally similar rearranged *ent*-kauranes, the jungermanenones (1205–1210) have been isolated also from an unidentified New Zealand

Jungermannia species (602, 609, 610). The French *J. exsertifolia* subsp. *cordifolia* produces *ent*-6,7-*seco*-kauranes (1176 and 1177) together with bis-*ent*-kaurene (1168) and *ent*-kauranes (1169–1175) (586). *ent*-Kaurane-type diterpenoids with a carboxylic acid group at C-10 (1188–1190) are characteristic for *J. rotundata* collected in Japan (588).

The Taiwanese *J. appressifolia* elaborates labdane-type triterpenoids, with (13*S*)-hydroxy-8,14-labdadiene (1240), labda-7,14-dien-9,13-diol (1273), and 13-hydroxy-7-oxolabda-8,14-diene (1274) having been isolated (952). Labdanes are also characteristic for *J. torticalyx* (39) and *J. appressifolia*, which have been classified in chemotype II.

There are two chemotypes of *J. truncata*: (I) the *ent*-kaurane type and (II) the *ent*-labdane type. The Malaysian, Taiwanese, and Japanese *J. truncata* produce *ent*-kaurene diterpenoids as major components (136, 477, 601). The Malaysian specimen produces not only kauranes but also pimarane- and halimane-type diterpenoids (136). Reinvestigation of the Japanese *J. truncata* afforded labdane-type diterpenoids (1237 and 1243) as the main compounds (569). No kauranes have been found in *J. truncata*. Thus, this species belongs to the second chemotype.

Clerodane diterpenoids are chemical markers of *J. hyalina*, which elaborates *ent*-3 β ,4 β -epoxycyclo-(13*E*)-en-15-ol (987), (3*R**,4*R**)-dihydroxycyclo-(13*E*)-en-15-al (988), and (3*R**,4*R**)-dihydroxycyclo-(13*Z*)-en-15-al (989), together with the halimane diterpenoid, 3 ζ -hydroxy-5(10),(13*E*)-halimadien-15-al (1126) (580). Compounds 988 and 989 and other clerodanes have been found in the English *J. paroica*, which is very similar morphologically to *J. hyalina* (40). Both species are classified in chemotype III.

The Japanese *J. comata* (type IV) produces almost exclusively (yield 58%) the bis-bibenzyl, perrottetin E (1638) (583), which is chemically very similar to the Japanese *J. infusca* collected in Kochi (587).

Jungermannia hattoriana and *J. rosulans* accumulate mainly cuparane-type sesquiterpenoids and labdane-type diterpenoids (type V) (524, 590). In addition to the compounds mentioned, the former species also elaborates the pimarane diterpenoid, *ent*-pimara-8(14),15-dien-19-oic acid (1325) (590).

The Japanese *J. vulcanicola*, collected in different locations, produces different compounds. A specimen collected in Nagano elaborated mainly *ent*-kaurane-type diterpenoids (570). Chiloscyphane-type sesquiterpenoids were found in specimen collected in Okayama, while labdane-type diterpenoids were obtained as the main components isolated from a sample collected in Shiga (585). Thus, there are at least three chemotypes of *J. vulcanicola* in Japan.

Nardia species are chemically very characteristic since they produce kaurane diterpenoids with a malonate moiety (e.g. 1231). These compounds have been found in *N. scalaris*, *N. subclavata*, and *N. succulenta* and are important chemical markers for *Nardia* species (39, 40). Other kauranes found in *Nardia* species are structurally very similar to those detected in *Jungermannia* species (40). Reinvestigation of the Japanese *N. subclavata* led to the isolation of kaurane malonate diterpenoids (1231–1233) together with *ent*-kaurene alcohols (1229 and 1230), the *ent*-clerodane, kolavelool (967), and an acyclic bis-bibenzyl, perrottetin E (1638) (84).

8.3.8.23 Myliaceae

In the new classification of the Marchantiophyta, *Mylia* was removed from the family, Jungermanniaceae, and placed in its own family, Myliaceae (168). The chemical evidence available supported this classification, especially the flavonoid chemistry. All studied *Mylia* species produce flavone di-*C*-glycosides, which are common among liverworts, but these compounds have proven to be absent in all *Jungermannia* species investigated (555).

Regarding their terpenoid chemistry, two chemotypes of *Mylia* species have been discovered so far. Type I (*M. nuda*, *M. taylorii*) contains aromadendranes and *seco*-aromadendranes, while type II (*M. anomala*, *M. verrucosa*) produces mainly cyathane-type diterpenoids.

Mylia taylorii is known as a rich source of *ent*-5,10-*cyclo*-aromadendranes (141–143) and *ent*-1,10-*seco*-aromadendranes (145–147) (922). In addition, the dimeric sesquiterpenoids, myltayloriones A (149) and B (150) have been isolated (569). *M. nuda* is characterized by having a very similar chemical composition to that of *M. taylorii*. Aromadendrane- and *seco*-aromadendrane-type sesquiterpenoids have been detected in this species (922). Besides the above-mentioned compounds, *M. nuda* also produces nudeonic acid (928) and its aldehyde (929), based on a new carbon skeleton (476). Both of these liverworts are also known for the presence of labdane-type diterpenoids (40).

Mylia verrucosa is a rich source of cyathanes belonging to the verrucosane type (39, 40). These compounds have also been found in *M. anomala* and *M. taylorii* (40).

8.4 Conclusion

Since the taxonomic classification of the Marchantiophyta is extremely difficult, especially that of leafy liverworts, studies of their chemical constituents have proven necessary to provide additional information from a chemosystematics point of view. Many liverworts produce their own particular constituents and some of these, such as the pinguisane- and sacculatane-type diterpenoids, have not been found in higher plants, fungi, or marine organisms (39, 40).

Liverwort species are characterized especially by large numbers of sesquiterpenoids. Several acyclic, mono-, bi-, and tricyclic sesquiterpene systems are present, including many unique combinations. Among them, sesquiterpene hydrocarbons like β -barbatene (235) and bicyclogermacrene (293) are the most widespread. Since sesquiterpene hydrocarbons are prevalent throughout liverworts and most liverwort species elaborate the same compounds, it is difficult to use these compounds as chemosystematic markers. However, other classes of sesquiterpenoids, such as cuparanes, eudesmanes, eremophilanes, germacrane, guaiane sesquiterpene lactones, pinguisanes, gymnomitranes, as well as sacculatane- and cyathane-type diterpenoids can be used as chemosystematic markers.

Monoterpenoids, responsible for their characteristic fragrances, occur mainly in thalloid liverworts belonging to the order Marchantiales, and some of these can be

used as chemical markers. Monoterpenes amounted to 77% of all compounds present in the volatiles of *Asterella venosa*. The main component found was geranyl acetate (**9**), a compound with a lemon-like odor ([492](#)). *Conocephalum conicum* also produces monoterpenoids as the main components, and, among these, sabinene (**44**) is the most prevalent compound ([492](#), [493](#)).

Aromatic compounds are also valuable chemosystematic indicators, especially bibenzyls and bis-bibenzyl derivatives. *Radula* species are an extremely rich source of prenylated bibenzyls. The most significant chemical indicators for this liverwort genus are 3,5-dihydroxy-2-(3-methyl-2-butenyl)bibenzyl (**1525**) and 2-geranyl-3,5-dihydroxybibenzyl (**1530**) ([39](#), [40](#)). In turn, the most important chemical markers of the family Marchantiaceae are the marchantin-type macrocyclic bis-bibenzyls, which have been found in all *Marchantia* species chemically investigated. Riccardin- and marchantin-type macrocyclic bisbibenzyls are characteristic compounds occurring in some *Riccardia* species, namely, *R. multifida*, *R. multifida* subsp. *decrescens*, and *R. nagasakiensis* ([40](#), [45](#)).

Although liverworts are a relatively small taxonomic group of plants, they produce many peculiar and uncommon compounds, which may be used as significant chemical markers for each liverwort genus and family. Cembranes and dolabellanes have been found in the genera *Barbilophozia* and *Chandonanthus*, classified in the Scapaniaceae. 2,3-*seco*-Aromadendranes and fusicoccanes are characteristic for the family Plagiochilaceae, herbertanes and herbertane dimers for the Herbertaceae and Mastigophoraceae, prenyl bibenzyls have been found in the Acrobolbaceae and Radulaceae, vibsanes in the genus *Odontoschisma* belonging to the Cephaloziaceae, long-chain alkyl phenols in the Schistochilaceae, azulenoids and chroman derivatives in the Calypogeiaceae, methyl benzoates with prenyl ethers in the Trichocoleaceae, pinguisanes in the Aneuraceae, Lejeuneaceae, Porellaceae, and Ptilidiaceae, eudesmanolides in the Frullaniaceae, benzyl and phenethyl methylthioacrylates in the Balantipsidaceae, monoterpenoids and their cinnamates in the Conocephalaceae, dumortanes in the Dumortieraceae, and marchantin-type bis-bibenzyls in the Marchantiaceae.

The identification of the chemical differences between liverworts is in agreement with molecular analysis concerning the phylogeny of the Marchantiophyta. Chemical data have supported the separation of *Frullania* from the Jubulaceae; the removal of *Jackiella* and *Odontoschisma* from Adelanthaceae; the unification of the Balantipsidaceae and Isotachidaceae; the removal of the Blasiaceae family from the order Metzgeriales and placement in the new order Blasiales within the complex thalloid hepatics; separation of the *Wiesnerella* from the Conocephalaceae to the independent Wiesnerellaceae family; removal of the *Symphyogyna* from the Hymenophytaceae to the Pallaviciniaceae; placement of the Pleuroziaceae in the independent order Pleuroziales within the subclass Merzgeriidae; exclusion of the *Neotrichocolea* and *Trichocoleopsis* from the Trichocoleaceae, and separation of *Mylia* from the Jungermanniaceae to its own Myliaceae family. One of the most significant developments in the classification of liverworts using chemical evidence was the unification of the Jungermanniales and the Metzgeriales ([39](#), [40](#), [45](#)).

9 Chemical Relationships Between Algae, Bryophytes, and Pteridophytes

The evolutionary origin of land plants (embryophytes) from their green algal ancestors was a pivotal event in the history of life (388, 533). Morphological and genetic studies have identified two distinct lineages within the green algae, termed Chlorophyta and Charophyta (114, 466). There is a concept that land plants descended from ancestral charophycean algae, and currently this theory is supported by molecular, biochemical, and ultrastructural evidence (388, 533). Red algae (Fig. 9.1) seem to be the most anciently emerged group among the eukaryotes 9–32) (469). The red and green algae sisterhood has been recently supported by molecular analysis (551). Phylogenetic studies have also been shown that heterokont algae (brown and yellow-green algae) possess red-algal plastids (462). However, the brown algae, in comparison to the green algae, are considered evolutionarily to be very different from the green plants (green algae, bryophytes, vascular plants) and are not closely related to each other, according to modern phylogenetic results (111).

Based on microfossil evidence it has been suggested that the liverworts are the earliest embryophyte lineage (937). Recent molecular phylogenetic studies concerning the early evolution of land plants has suggested strongly the liverworts are the sister of all other land plants. Hornworts have been described as the sister to vascular plants, while mosses were placed between the liverworts and the hornworts. These results also highlighted the important roles of liverworts and hornworts in two major events of plant evolution: the water-to-land transition and the change from a haploid gametophyte generation-dominant life cycle in bryophytes to a diploid sporophyte generation-dominant life cycle in vascular plants (665).

From this point of view, the chemical interrelationship between algae, bryophytes (liverworts, mosses and hornworts), and ferns is very interesting. Taking into account the chemistry of all the above-mentioned groups of plants, we describe below some chemo-evolutionary convergences between algae and bryophytes, bryophytes and pteridophytes as well as relationships within bryophytes, and between liverworts, mosses, and hornworts.



Fig. 9.1 Red alga (*Desmia japonica*)

9.1 Similarities Between Liverworts, Mosses, and Hornworts

It has been considered for a very long time that the Marchantiophyta are not chemically related to the Musci because of the absence of oil bodies in the latter. However, recent chemical analysis of some mosses has indicated that *Plagiomnium acutum* produces the *ent*-sesquiterpene hydrocarbons, (–)- β -cedrene (432), α -cedrene (430), and α -acoradiene (68) as well as the dolabellane diterpenoid, (+)-dolabella-3,7-dien-18-ol (2063), which have also been found in liverworts (884). Saritas and colleagues identified many kinds of common mono-, sesqui-, and diterpenoids in several mosses including *Homalia*, *Mnium*, *Plagiomnium*, *Plagiothecium*, and *Taxiphyllum* species (708). The ether extracts of 13 mosses belonging to the Mniaceae family have also been analyzed by GC/MS, and a few common sesqui-, di-, and triterpenoids have been detected (784). The presence of the pimarane-type diterpene lactones, momilactone A (2064) and B (2065), has been confirmed in the moss *Hypnum plumaeforme* (628).

In comparison to mono- and sesquiterpenoids, mosses are rich in triterpenoid compounds. The presence of cycloartane, fernane, friedelane, hopane, lupane, obtusifolane, taraxane, and ursane triterpenoids has been reported (40). Other studies have reported the isolation of polypoda-7,13,17,21-tetraene (2072) together with diploptene (1435) and the dammarane-type triterpene hydrocarbon, 2071, from *Floribundaria aurea* ssp. *nipponica* (885), and the serratane triterpenoids 2075–2077 from *Homalia trichomanoides* (926). 21 α -Methoxyserrat-14-en-3-one (1460) has been isolated from the liverworts *Plagiochila asplenoides* and *Nardia scalaris* (40, 604). Triterpenoids of this type were isolated originally from club

mosses (Lycopodiaceae) and also occur in ferns (Polypodiaceae) and quite often in conifers.

The simple aromatic compounds, benzyl benzoate (**1829**), diphenylamine (**2110**), and methyl *p*-hydroxybenzoate (**2080**), among others, have been isolated from the Egyptian moss *Eucladium verticillatum* (**3**). Benzyl benzoate (**1829**) is a compound that occurs in liverworts, in the genus *Isotachis*, such as in *I. layllii* and *I. japonica* (**40**, **73**). Methyl *p*-hydroxybenzoate (**2080**) has not been found in liverworts, but the presence of *p*-hydroxybenzoic acid (**2079**) and vanillic acid methyl ester (**1746**) has been confirmed in *Asterella lindenbergiana* and *Trichocolea pluma* (**157**, **490**, **494**).

Nitrogen-containing compounds in bryophytes are quite rare. Prenylated indole derivatives (**2199** and **2200**) have been found in the liverwort genus *Riccardia* (**39**, **40**, **56**), while *Metzgeria rufula* biosynthesizes rufulamide (**1887**), an oligopeptide analogue combined with malonic and anthranilic acid (**446**). The presence of isothiocyanates **1882** and **1883** and (*S,S*)-dimethyl iminodithiocarbonates **1884** and **1885** has been confirmed in *Corsinia coriandrina* (**921**). The alkaloid harmol (**2109**), its propionic acid derivative (**2108**), and the amino acid derivative, fontinalin (**2107**), have been isolated from the watermoss *Fontinalis squamosa* (**704**).

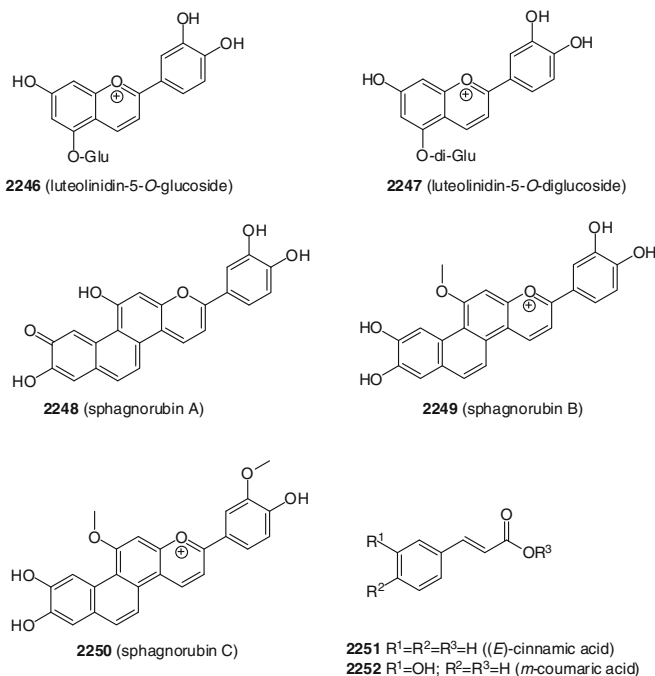
From the moss *Homalia trichomanoides*, atranorin (**1838**) and atraric acid (**1738**) have been obtained (**926**). The same compounds have been detected in the liverworts, *Frullania brasiliensis* (**98**) and *Trocholejeunea sandvicensis* (**460**). It is noteworthy that atranorin (**1838**) is known as a lichen component that causes allergies (Lahlou *et al.* 200b).

The most characteristic feature of mosses is the presence of flavonoids. These plants have evolved to produce mono-, bi-, and tri-flavonoids. In particular, the presence of bi- and tri-flavonoids is most characteristic of mosses (**250**). The Marchantiophyta, in comparison to the Bryophyta, produce monoflavonoids, which are usually *C*- or *O*-glycosides. Flavone-*C*-glycosides are regarded as phylogenetically “primitive” compounds and occur especially in simple thalloid liverworts. Leafy and complex thalloid liverworts produce mainly flavone-*O*-glucuronides (**509**). *Takakia*, originally described as liverwort genus, seems to be among the most primitive of mosses, possessing many characters similar to those of the liverworts, and is the only known genus of its class, having two species (**675**). This moss taxon contains a high concentration levels of a wide variety of flavone *O*-glucuronides, flavone *C*-glycosides, and flavonol *O*-glycosides (**516**). The flavonoids of *Takakia* are most closely related to those found in *Hymenophyton* species. However, the range of flavonoid types is in fact the most extensive yet found in any liverwort genus. The diversity and abundance of flavonoids found in these liverworts are rather similar to those of mosses, although bis-flavonoids have not been found in *Takakia*. Thus, the genus *Takakia* exemplifies the close relationship between liverworts and mosses.

Chemical analysis of *Chandonanthus hirtellus* subsp. *giganteus* led to the isolation of dicranolomin (= 2',6''-bisluteolin) (**1909**) (**441**), a biflavone first detected in the moss *Dicranoloma robustum* (**250**). This is the first report of the

presence of bis-flavonoids in this liverwort, and such a chemical identity supports the position of mosses as the sisters to liverworts (665).

Mosses are also known to produce anthocyanins. The 3-deoxyanthocyanins, luteolinidin-5-*O*-glucoside (2246) and luteolinidin-5-*O*-diglucoside (2247), occur in *Bryum cyclophyllum*, *B. rutilans*, and *B. weigellii* (40). Three red pigments, sphagnorubins A, B, and C (2248–2250) have been found in *Sphagnum* species (40). The anthocyanidins, riccionidin A (1934) and a dimer, riccionidin B (1935), have been isolated from the liverwort *Ricciocarpos natans*, and also detected in *Marchantia polymorpha*, *Riccia duplex*, and *Scapania undulata* (454).



Anthocyanins found in the moss, *Bryum* and *Sphagnum* species, and cinnamic acid and *m*-coumaric acid in *Brachythecium* and *Mnium* species

Hornworts are the third group belonging to the bryophytes, and, like mosses, these plants do not possess oil bodies, and are considered as being poor in terpenoid metabolites. However, *Mekem Sonwa* and *König* (540) identified several kinds of common mono-, sesqui-, and diterpenoids in the essential oil of the hornwort *Anthoceros caucasicus*. It is noteworthy that this hornwort produces veticadin oxide (2166) (540), for which the structure is very similar to that of gongylantoxide (2243) isolated from the liverwort *Gongylanthus ericetorum* (40, 45) (see Sect. 8.3.8.16).

Methyl *p*-coumarate (2169a) has been isolated from the hornworts, *Anthoceros laevis* and *A. punctatus*. The former species also produce caffeic acid methyl ester (1867) (545). Additionally, *Takeda* and colleagues described the isolation of rosmarinic acid (2170) and lignans from the two hornworts, *Anthoceros punctatus*

and *Megaceros flagellaris* (800). Rosmarinic acid (2170), together with its glucoside (2171) and isorinic acid (2172), is found also in *Anthoceros agrestis* (917). Cinnamic acid derivatives are known to occur in liverwort species. Compound 1867 and ferulic acid methyl ester (1868) have been found in the sporophytes of *Pellia epiphylla* (175), while (*E*)-methyl cinnamate (1836) has been detected in *Conocephalum conicum* (880). Benzyl (*E*)-cinnamate (1833), together with β -phenethyl (*E*)- (1835) and (*Z*)-cinnamates (1834), has been isolated from *Isotachis* species and *Balantiopsis cancellata* (73, 288, 457). *Jungermannia subulata*, *Lophocolea heterophylla*, and *Scapania parvixeta* produce subulatin (1864), a caffeic acid derivative (823). (*E*)-Cinnamic acid (2251) has been detected in the mosses *Brachythecium rybatulum* and *Mnium hornum*, together with caffeic (2085), *p*-coumaric (2086), and *m*-coumaric (2252) acids (40).

From *in vitro* cultures of *Anthoceros agrestis*, the alkaloid anthocerodiazonin (2173) and glutanic acid amines (2174–2179) have been isolated (902). Nitrogen-containing compounds are quite rare in bryophytes. However, some prenylated indole derivatives have been found in *Riccardia* species (40) and alkaloids in the water moss *Fontinalis aquamosa* (704).

The fatty acid composition among bryophytes (liverworts, mosses, and hornworts) is quite similar. The major components are 18:3n-3 (2017) and 16:3n-3 acids (2008). They are also known to produce C₂₀ polyunsaturated fatty acids, among which 20:5n-3 (2026) and 20:4n-6 acid (2023) are predominant (730, 731).

From the hornwort *Megaceros flagellaris*, the phytyl esters 2167 and 2168 and phaeophytins (*e.g.* 2043, 2044), together with sitosterol (1426) and stigmasteryl hexadecanoate (1423), have been isolated (140). The phaeophytins, 2043–2046, which represent chlorophyll derivatives, have also been found in the liverwort *Plagiochila ovalifolia* (529) and in the moss *Entodon rubicundus* (40). Sterols and triterpenoid esters with fatty acids have been isolated from the liverworts, and also detected in the pteridophytes (see Sect. 9.3)

9.2 Similarities Between Algae and Bryophytes

Phylogenetic studies suggest that *Nitella* species, of the class Charophyceae, may be direct precursors to land plants like green algae (345). *Nitella hookeri* has been found to produce flavonoid C-glycosides (515). These flavonoids with phylogenetically “primitive” characters have been isolated from a number of liverworts, especially simple thalloid liverworts (509).

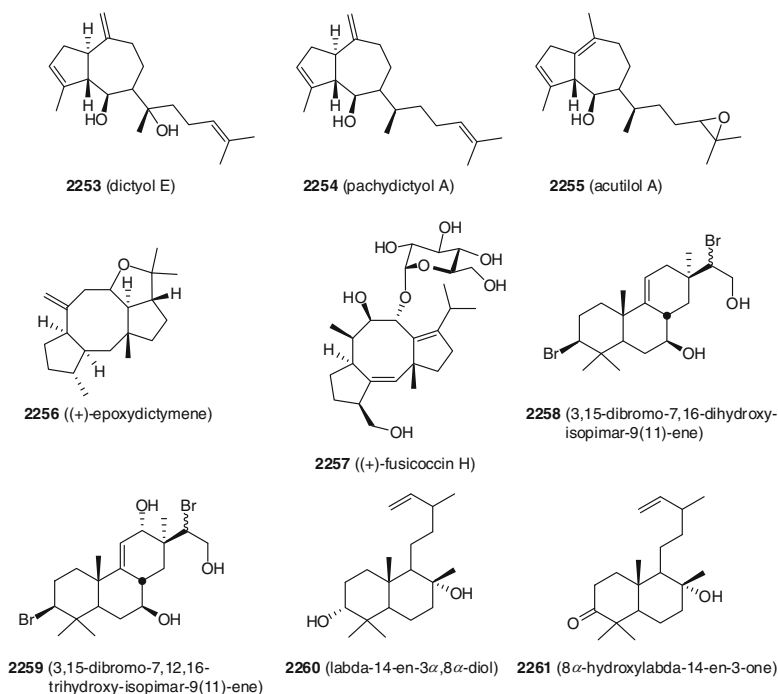
Dimethyl sulfide (DMS) is a component of the “smell of the sea”. Many marine algae, such as the green alga, *Ulva fenestra*, and the red alga, *Polysiphonia hendryi*, biosynthesize dimethylsulfoniopropionate (DMSP), which is the precursor of DMS (912). Interestingly, DMS has been found in the liverworts *Porella cordaeana* and *Plagiochila sciophila* (40, 863).

Other compounds responsible for an “ocean smell” are algal pheromones called dictyopterenes. These pheromones, occurring in brown algae, are lipophilic and volatile compounds consisting of C₈ or C₁₁ linear or monocyclic hydrocarbons or their epoxides (416).

Fossombronia angulosa, collected in Greece, produces dictyopterenes previously reported in brown algae belonging to the genus *Dictyopteris* (383), as the main components. Dictyotene (1936), (Z)-ectocarpene (1938), and dictyopterene (1939) have been reported (492, 919). Recently, dictyotene (1936) and (E)-ectocarpene (1937) have also been found in *Chandonanthus hirtellus* collected in Tahiti (494). The marine algal components of *Fossombronia* species are extremely interesting since the species is similar morphologically to certain marine algae, e.g. *Ulva* species. *Chandonanthus* is a leafy liverwort belonging to the family Scapaniaceae, but both species have been placed phylogenetically in the Jungermanniopsida class of liverworts.

There are many other chemical features that make liverworts similar to algae. *Saccogyna viticulosa* produces viticulol (1415), a prenylguaiane-type diterpenoid (276). Such compounds are found mainly in brown algae of the genera *Aplysia*, *Cystoseira*, and *Dictyota* (87, 128). Examples are dictyol E (2253) and pachydictyol A (2254) or acutilol A (2255). The tendency to accumulate viticulol (1415) may be considered as another example of a phylogenetic relationship between bryophytes and algae. Prenylguaianes, together with dolabellanes and other diterpenoids, are chemosystematic markers of brown algae in the genus *Dictyota* (824). Among the wide array of marine diterpenoids, the dolabellanes constitute one of the principal groups. Mainly brown algae, sea hares, soft corals, and gorgonians produce these diterpenoids; they have also been found in liverworts. The presence of dolabellane-type diterpenoids (1085–1093) is the most characteristic chemical feature of *Odontoshisma denudatum* (316, 317, 319, 326). Such compounds have been reported also from other liverworts, namely, *Barbilophozia* species, *Chandonanthus hirtellus*, *Pleurozia gigantea*, and *Plagiochila sciophila* (40, 326, 583, 927). There is also one example of the presence of dolabellanes in mosses. From the Japanese *Plagiomnium acutum*, (+)-dolabella-3,7-dien-18-ol (2063) has been isolated (884).

The dolabellane ring system has a pivotal position in the biogenesis of several diterpene skeletons, such as the fusicoccanes. The fusicoccane diterpenoids are postulated products of efficient stereo-controlled transanular transformations of dolabellanes (683). These compounds have been detected in many liverwort species. A remarkably rich source of fusicoccane-type diterpenoids are the *Plagiochila* species, but such compounds have also been found in *Barbilophozia* species, *Chandonanthus hirtellus*, *Pleurozia gigantea*, *Frullania* species, *Anastrophyllum auritum*, *Lepicolea ochroleuca*, and *Bryopteris filicina* (see Table 4.3). Fusicoccane-type diterpenoids are also known as components occurring in algae and fungi. (+)-Epoxydictymene (2256) from the brown alga *Dictyota dichotoma* (207), (–)-fusicoplagin A (1112) from the liverwort *Plagiochila acanthophylla* (40), and (+)-fusicoccin H (2257) from the fungus *Phomopsis (Fusicoccum) amygdali* (710), are selected representatives. The red alga *Laurencia perforata* produces the brominated pimarane-type diterpenoids, 2258 and 2259 (261). Among liverworts, pimaranes, especially diterpenoic acids of the pimarane type, have been found in *Herbertus sakuraii*, *Mastigophora diclados*, *Jamesoniella kirkii*, *Cuspidatula monodon*, and *Plagiochila deltoidea* (72, 287, 365, 607, 612).



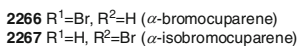
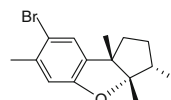
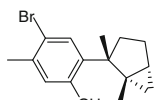
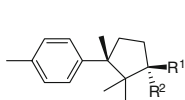
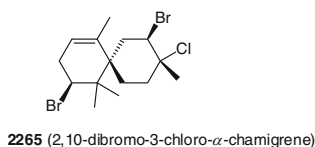
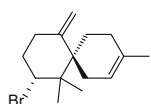
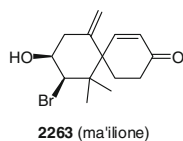
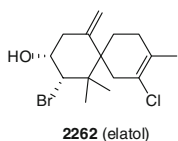
Fusiccocane-type diterpenoids found in brown algae, fusiccocin H from a fungus, brominated isopimarane-type diterpenoids in the red alga, *Laurencia perforata*, and labdane-type diterpenoids from the green alga, *Ulva fasciata*

Algae, especially brown algae as well as liverworts, are rich sources of diterpenoids. However, very recently labdane-type diterpenoids have also been found in the green alga, *Ulva fasciata*. From the dichloromethane extract, *Chakraborty* and colleagues isolated seven compounds, inclusive of labda-14-ene-3 α ,8 α -diol (**2260**) and labda-14-ene-8 α -hydroxy-3-one (**2261**), which showed antibacterial activity ([151](#)). Among liverworts, labdanes have been detected in or isolated from *Jungermannia* species, *Jamesoniella* species, *Ptychanthus striatus*, *Blepharostoma trichophyllum*, *Pallavicinia subciliata*, *Scapania undulata*, and many others (see Table 4.3).

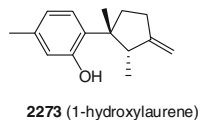
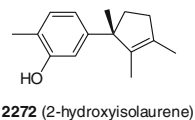
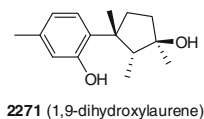
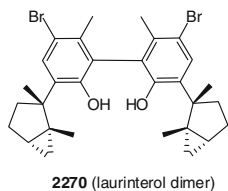
A diterpene possessing a new skeleton, hatcherenone (**1419**), has been found in *Barbilophozia hatcheri* ([593](#)). Hatcherenone (**1419**) might be biosynthesized from geranylgeranyl diphosphate *via* the xenicane-type diterpenoids. Xenicanes occur in many marine organisms including algae, especially brown algae belonging to the family Dictyotaceae.

Algae and liverworts are also known to produce cuparane- and chamigrane-type sesquiterpenoids. Large numbers of these types of sesquiterpenoids are found in marine algae and possess carbon-halogen covalent bonds, especially bromine-carbon bonds. Halogenated chamigranes and cuparanes are widespread among red algae in the genus *Laurencia*. Elatol (**2262**) and ma'ilione (**2263**), from *L. cartilaginera* ([380](#)), and 10-bromo- β -chamigrene (**2264**) and 2,10-dibromo-3-chloro- α -chamigrene

(**2265**), from *L. nipponica* (**496**), are representative chamigranes. *L. grandulifera* and *L. okamurai* produce α -bromocuparene (**2266**) and α -isobromocuparene (**2267**). In the latter species, the cuparene-derived laurinterol (**2268**) and aplysin (**2269**) have been detected (**789, 793**). Interestingly, *L. microcladia* produces a laurinterol dimer (**2270**) (**414**), which is structurally very similar to aquaticenol (**491**) isolated from the liverwort, *Lejeunea aquatica* (**878**) and mastigophorenes A (**528**) and B (**529**), found in *Herbertus* and *Mastigophora* species (**40**). It is worth mentioning that cuparene-derived lauranes, e.g. laurinterol (**2268**) and aplysin (**2269**), have also been found in the marine green alga, *Chaetomorpha basiretorsa* (**736**).



Halogenated chamigrane- and cuparene- and rearranged cuparene-type sesquiterpenoids found in the red algae, *Laurencia* species

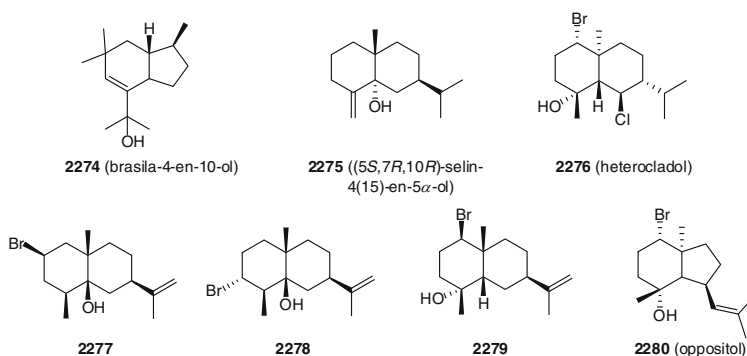


Cuparene dimer and rearranged cuparene-type sesquiterpenoids found in *Laurencia* species

There are also some nonhalogenated sesquiterpenoids found in algae. 1,9-Hydroxycuparene (**2271**), 2-hydroxyisolaurene (**2272**), and 1-hydroxylarene (**2273**) are representatives of cuparanes and lauranes occurring in *Laurencia* species (**414**).

Germacrane (*e.g.* (–)-germacrene D (**692**)), cubebane (*e.g.* (+)-cubebol (**462**)), cadinane (*e.g.* (+)- δ -cadinene (**348**), and cubenol (**357**)) and (+)- β -elemene (**283**), which are widespread in liverworts, have been detected in brown algae from the genera *Dictyota*, *Dictyopteris*, and *Taonia* (**383**, **186**, **749**, **790**). From the leafy liverwort *Barbilophozia floerkei*, the germacrane-type sesquiterpene alcohol (1*S*,7*R*)-germacra-4(15),5,10(14)-trien-1-ol (**696**) has been isolated (**583**), while the brown alga, *Dilophus fascicola*, produces an acetate, for which the optical rotation is same as found in the alcohol from the above-mentioned liverwort (**211**). It is noteworthy that the signs of the specific rotations of compounds isolated from brown algae and liverworts are, not only in this case, but also in many other cases, the same. Examples are (+)-cubebol (**462**) from the brown alga, *Dictyopteris divaricata* (**790**) and from the liverwort, *Preissia quadrata* (**433**), and (+)- δ -cadinene (**348**) from the above-mentioned alga species (**790**), and from the liverwort *Calypogeia muelleriana* (**933**). The occurrence of the same compounds with the same signs of specific rotation in brown algae and liverworts is of significance, since 80% of compounds isolated from the liverworts are enantiomers of the same substances when found in higher plants (**39**, **40**, **45**).

The red alga, *Laurencia implicata* and *L. obtusa*, elaborate brasilane-type sesquiterpenoids (**363**, **948**). The former species produces brasila-4-en-10-ol (**2274**), for which the structure is similar to that of conocephalenol (**345**) isolated from the thallose liverwort, *Conocephalum conicum* (**841**). From the essential oil of *Marsupella alpina*, (–)-*trans*-selina-4(15),11-dien-5 β -ol (**587**) has been isolated (**17**). A similar compound, (5*S*,7*R*,10*R*)-selin-4(15)-en-5 α -ol (**2275**), which exhibits the opposite configuration to compound **587**, has been found in the red alga, *Laurencia nipponica* (**791**). A eudesmane possessing bromine and chlorine atoms, heterocladol (**2276**), has been detected in the red alga, *Laurencia filiformis*. This compound is the antipode of similar eudesmane sesquiterpenoids isolated from vascular plants (**401**). Three brominated eudesmane-type sesquiterpenoids (**2277**–**2279**) have also been isolated from the tropical green alga, *Neomeris annulata* (**270**).

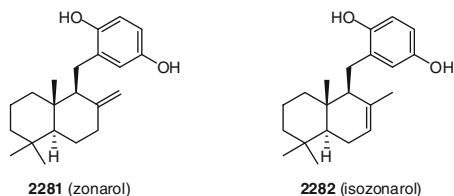


Brasilane- and *ent*-eudesmane sesquiterpenoids found in the red alga, *Laurencia implicata*, brominated eudesmanes from the green alga, *Neomeris annulata*, and an oppositane-type sesquiterpenoid from the red alga, *Laurencia subopposita*

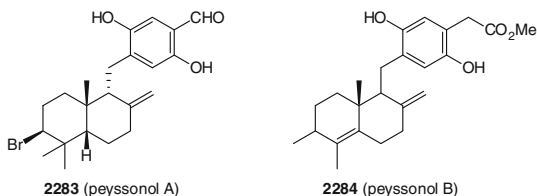
Chiloscyphus pallescens elaborates oppositane-type sesquiterpenoids together with biogenetically related chiloscyphanes (**40**). Oppositanes and chiloscyphanes

have also been found in a different specimen of *C. rivularis* (956). A very similar, oppositane-type brominated sesquiterpene alcohol, oppositol (2280), has been isolated from the red alga *Laurencia subopposita* (284).

Very characteristic sesquiterpenoids possessing the drimane skeleton substituted with a hydroquinone moiety, *e.g.* zonarol (2281) and isozonarol (2282), have been found in the brown algae *Dictyopteris* species (218). Peyssonol A (2283) and the closely related peyssonol B (2284) have also been detected in the red algae, *Peysoniella* species (802). Drimanes are very characteristic components found in the liverworts. In particular, they are diagnostic compounds of *Porella* species classified in the drimane-type chemotype belonging to the *Porella vernicosa* complex (39, 40, 45). *Bazzania* species are known to produce drimane-type sesquiterpene esters (*e.g.* 541, 542) (40, 291, 821).

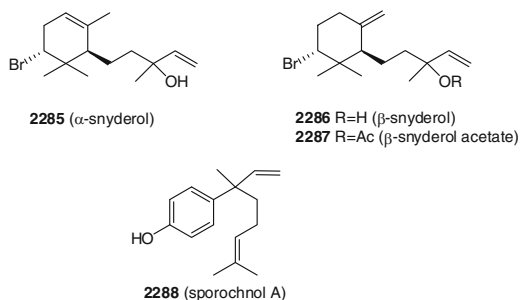


Drimane-type sesquiterpene derivatives found in brown algae



Drimane-type sesquiterpene derivatives found in red algae

Red algae as well as liverworts produce monocyclofarnesane-type sesquiterpenoids. Isomeric α - (2285) and β -snyderols (2286) have been isolated from *Laurencia obtusa*, while the latter compound and its acetate (2287) are contained in *Laurencia snyderae* (191). A debrominated β -snyderol derivative, named β -monocyclonerolidol (805), has been isolated from the liverworts *Archilejeunea olivacea*, *Ptychanthus striatus*, and *Spruceanthus polymorphus* (40, 882).



Monocyclofarnesane-type sesquiterpenoids found in red algae and sporochinol A found in a brown alga

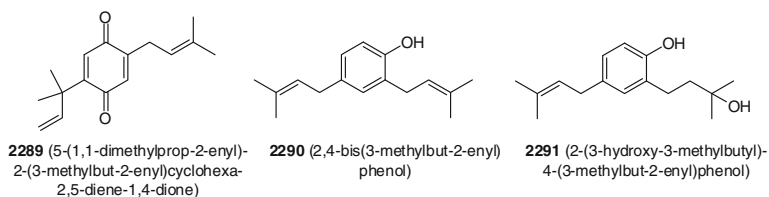
Cheilolejeunea serpentina produces the very characteristic phenolic sesquiterpenoid, serpentiphenol (**2214**) (40). The structurally similar compound, sporochinol A (**2288**), has been found in the brown alga, *Sporochnus bolleanus* (734).

Loliolide (**2042**), a C₁₁-terpene lactone that arises from biological or oxidative degradation of carotenoids, has been isolated from both terrestrial plants and marine algae. Among the liverworts, compound **2042** has been found in *Pellia epiphylla* (176). Compound **2042** has been isolated from the brown alga *Cladostephus spongiosus* f. *verticillatus* (204), and, together with another loliolide derivative, β -ionone (**2052**), has been found in the brown alga *Undaria pinnatifida* (412). Loliolide (**2042**) also occurs in the green alga, *Chaetomorpha basiretorsa* (735).

Algae, as well as liverworts, are known to produce lunularic acid (**1478**), a growth inhibitory agent. This compound has been found in green (e.g. *Ulva lactusa*), brown (e.g. *Fucus ceranoides*), and red algae (e.g. *Chondrus crispus*) as well as in blue-green and yellow-green algae; however, it has been not detected either in mosses or in ferns. On the other hand, a second growth inhibitor, abscisic acid (**812**), has not been detected in algae, but is known to occur in pteridophytes and mosses and is of general occurrence in higher plants (663). Among liverworts, compound **812** has been found only in *Marchantia polymorpha* (467). The occurrence of **1478** in algae and liverworts seems to be substantial chemical evidence that the Marchantiophyta are the most ancient terrestrial plants (663).

The liverwort *Schistochila appendiculata* is characterized by the presence of long-chain alkylphenols like 3-undecylphenol (**1874**), 3-tridecylphenol (**2222**), 6-tridecylsalicylic acid (**2223**), and 6-undecylcatechol (**1875**) (40). 3-Tridecylphenol (**2222**) and 6-tridecylsalicylic acid (**2223**) have also been found in the brown alga *Caulocystis cephalornithos* (400).

Plagiochila rutilans elaborates the hydroquinone derivatives **1802–1805** as prominent components (693). The bis-prenylated quinone, **2289**, which is chemically similar to 2-methoxy-6-(3-methyl-2-butenyl)-1,4-benzoquinone (**1803**), has been found in the brown alga, *Perithalia capillaris* (706). From the brown alga *Encyothalia cliftonii*, the two bis-prenylated phenols, **2290** and **2291**, have been isolated (685). These compounds resemble the bis-prenylated bibenzyl derivatives found in *Lethocolea glossophylla*, as, for example, **1537** (447).

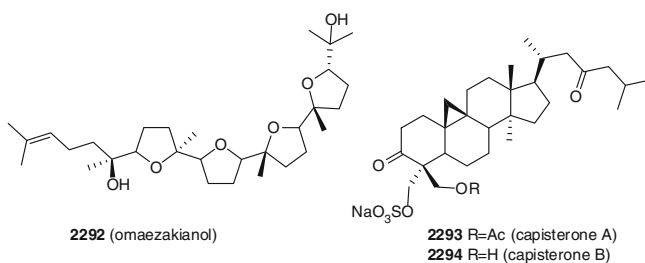


A bis-prenyl benzoquinone and bis-prenylphenols found in brown algae

The presence of triterpenoids is quite rare in liverworts and algae. Red algae belonging to the genus *Laurencia* elaborate squalene-derived triterpene polyethers, such as omaezakianol (**2292**) from *L. omaezakiana* (530). Cycloartane-type

triterpenoids are characteristic components of green algae, however, they also occur in red alga species (354, 664, 981). Cycloart-23-en-3 β ,25-diol (1462) and cycloart-25-en-3 β ,24 ξ -diol (1463) have been isolated from the liverwort *Dendromastigophora flagellifera* (635). Both compounds have also been found in the green alga *Cladophora fascicularis* (354). A mixture of cycloartenyl esters with eicosapentaenoic and 11,14-octadecadienoic acid moieties (1455, 1457), has been detected in the liverwort *Mastigophora diclados* (287), while the green alga *Penicillus capitatus* produces the cycloartenyl sulfate esters 2293 and 2294 (664).

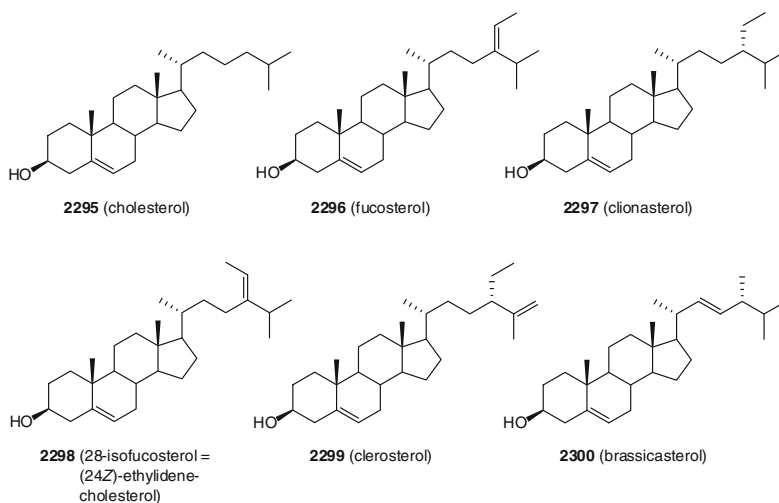
Sterols are components of nearly all living organisms. Among algae, cholesterol (2295) is the primary sterol of red algae, while fucosterol (2296) dominates in brown algae. The primary sterols of the Charophyta appear to be clionosterol (2297), the 24 β isomer of sitosterol, and 28-isofucosterol (2298) (642). Green algae belonging to the family Ulvaceae produce 28-isofucosterol (2298) as the main sterol (184), while in *Codium fragile* the principal component is clerosterol (2299) (38). Higher plants generally contain sitosterol (24-ethylcholesterol) (1426), possessing the 24 α -alkyl configuration (643). The situation with respect to the 24-methylsterols is similar. Algae elaborate the 24 β -methyl epimers, e.g. brassicasterol (2300), while higher plants biosynthesize epimeric mixtures of 24 α - and 24 β -methylsterols, in which the 24 α form is predominant (155, 643). The phytosterol composition of bryophytes, especially liverworts, suggests that these plants are in evolutionary transition between algae and higher plants, since they produce both alga1 (24 β -alkyl) and higher plant (24 α -alkyl) sterols. 24-Methylcholesterol, 24-ethylcholesterol, and 24-ethyl-5, 22-cholestadienol are the major sterols occurring in bryophytes. All of these are usually mixtures of 24 α and 24 β epimers (155). In the case of 24-ethylcholesterol, some bryophytes produce only the 24 α -ethyl epimer, 1426, like *Conocephalum conicum* and *Plagiomnium succulentum*. However, other species also contain clionosterol (2297), such as *Marchantia polymorpha* (50%) and *Sphagnum palustre* (16%) (155, 643). All of the 24-methylcholesterol samples from bryophytes are epimeric mixtures. Some of these have a 24 α /24 β ratio of approximately 2:1, as is typical in higher plants, but in *Mastigophora diclados* a ratio of approximately 1:1 is evident (155).



Triterpene polyether and cycloartane-type triterpenes found in red and green algae

The lipids of bryophytes are broadly similar to those of higher plants, but there are some features demonstrating a chemical link with algae rather than

higher plants. This is the presence of arachidonic (20:4n-6) (**2023**) and eicosapentaenoic (20:5n-3) (**2026**) acids. The ability to synthesize highly unsaturated fatty acids by algae and bryophytes is a major biochemical difference between lower plants and angiosperms (*157, 389*). A greater range of fatty acids than in higher plants is also a characteristic of both algae and bryophytes. Olefinic acids of the C₁₄, C₁₆, C₁₈, C₂₀, and C₂₂ series amount to over 70% of the total acids present in algae and polyolefinic acids with up to five double bonds predominating. The major acids are polyolefinic acids, which are usually highly unsaturated. In Rhodophyta species, the main compound is eicosapentaenoic acid (20:5n-3) (**2026**), while arachidonic acid (20:4n-6) (**2023**) is the major fatty acid in the Phaeophyta. In Chlorophyta, the C₂₀ acids are present in smaller amounts than in red and brown algae. The major acids are 16:0 (**1982**), 16:4n-3 (**2011**), 18:1n-9 (**2002**), 18:3n-3 (**2017**), and 8,11,14-octadecatrienoic acid (18:3n-4) (*374*). A very similar composition of fatty acids has also been found in bryophytes. The main acids detected in *Lophocolea heterophylla* are palmitic (16:0) (**1982**), oleic (18:2n-9) (**2002**), and linoleic (18:3n-6) (**2012**), together with the C₂₀ highly unsaturated acids (20:5n-3) **2026** and (20:4n-6) **2023** (*832*). In the thalli of *Marchantia polymorpha*, the 18:3n-3 acid **2017** is predominant, but significant amounts of the 20:5n-3 (**2026**) and 20:4n-6 (**2023**) acids have also been detected (*188*). The most characteristic feature of the lipids in liverworts is the presence of large amounts of acetylenic fatty acids. The neutral and phospholipid fractions from *Marchantia polymorpha* yielded 22.6% and 8.5% acetylenic compounds (*188*), while the triacylglycerols of *Riccia fruitans* yielded 80.2% (*190*). Acetylenic fatty acids have also been found in mosses, and some of them, as in the liverworts, are characterized by significant concentration levels of these acids, *e.g.* *Dicranum polysetum* – 72.1% and *Fontinalis antipyretica* – 63.0% (*189, 190*).

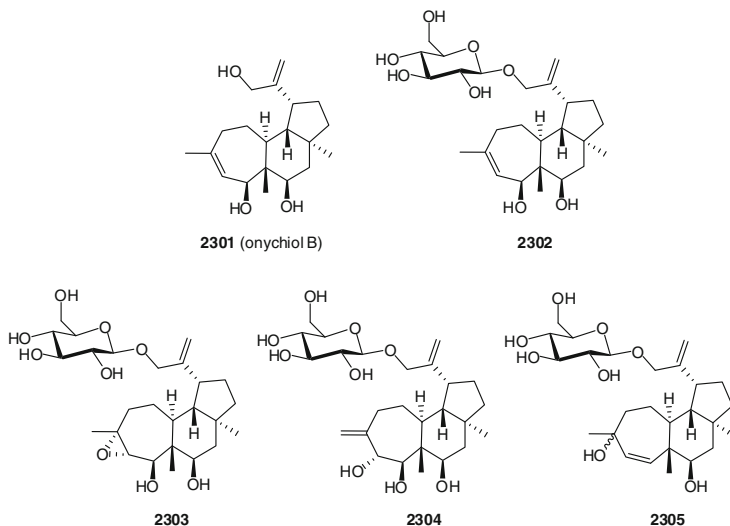


Phytosterols found in green, brown, and red algae

9.3 Similarities Between Bryophytes and Pteridophytes

The New Zealand fern *Blechnum fluviatile* produces drimane-type sesquiterpenoids, such as polygodial (**548**), which are also very characteristic compounds occurring in the *Porella* genus of liverworts belonging to chemotype I (see Sect. 8.3.6.1). Drimane-type sesquiterpenoids have also been found in two other fern species, *Nephrolepis biserrata* and *Thelypteris hispida* (**754**, **761**).

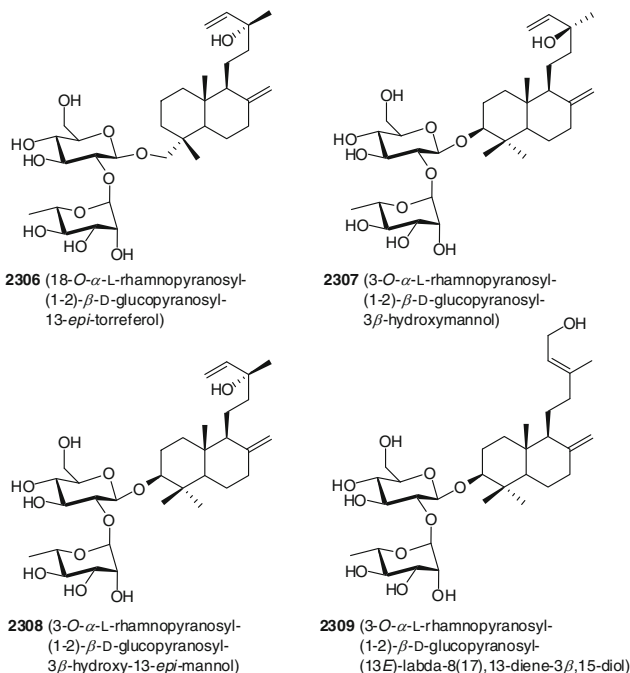
From the Japanese fern *Onychium japonicum*, the cyathane-type diterpene glycosides **2302**–**2305** have been isolated (**37**), while non-glycosylated compounds are also known, such as onychiol B (**2301**) (**350**). Cyathanes are compounds known to occur in the liverworts. They have been detected among the *Fossombronia* (**269**, **492**) and *Plagiochila* and *Jamesoniella* species (**32**, **872**, **910**). Besides cyathanes, labdane- and clerodane-type diterpenoids have been found also in ferns. The labdane-type diterpenoid glycosides, **2306**–**2309**, have been isolated from the Japanese fern *Gleichenia japonica* (**744**). The same fern and *Dicranopteris pedata* also produce the clerodane glycosides, **2310**–**2314** (**35**, **751**). Labdanoids and clerodanes are widespread in liverworts (see Table 4.3), however, no glycosylated compounds have been detected, except for the presence of *ent*-kaurane glucosides (**40**). It is interesting to note that most of the diterpenoids found in ferns were isolated in the form of glycosides.



Cyathane-type diterpenoids found in the fern, *Onychium japonicum*

Triterpenoid constituents found in ferns are quite similar to those of mosses. From the moss *Floribundaria aurea* ssp. *nipponica*, polypoda-7,13,17,21-tetraene (**2072**) has been isolated (**885**). The same compound has been isolated from the ferns *Polystichum ovatopaleaceum*, *P. polyblephalum*, and *Cheiropleuria bicuspis* (**384**, **743**). Some ferns and mosses also produce dammarane (**743**),

hopane, and serratane triterpenoids (21) (see Sect. 8.1), as well as euphane or malabaricane triterpenoids, among others (384). The fern *Polypodium polypodioides* is known to produce the cycloartanoid alcohol linoleates 2315–2317 (21). Cycloartanoid esters with palmitic, linoleic, and linolenic acid units have been isolated from the fern *Cheiropleuria bicuspsis* (384). Interestingly, triterpenoid esters with fatty acid moieties, including cycloartanoid esters such as 1454, 1456 and 1457, have also been found in the liverwort *Plagiochila circinalis* (898).

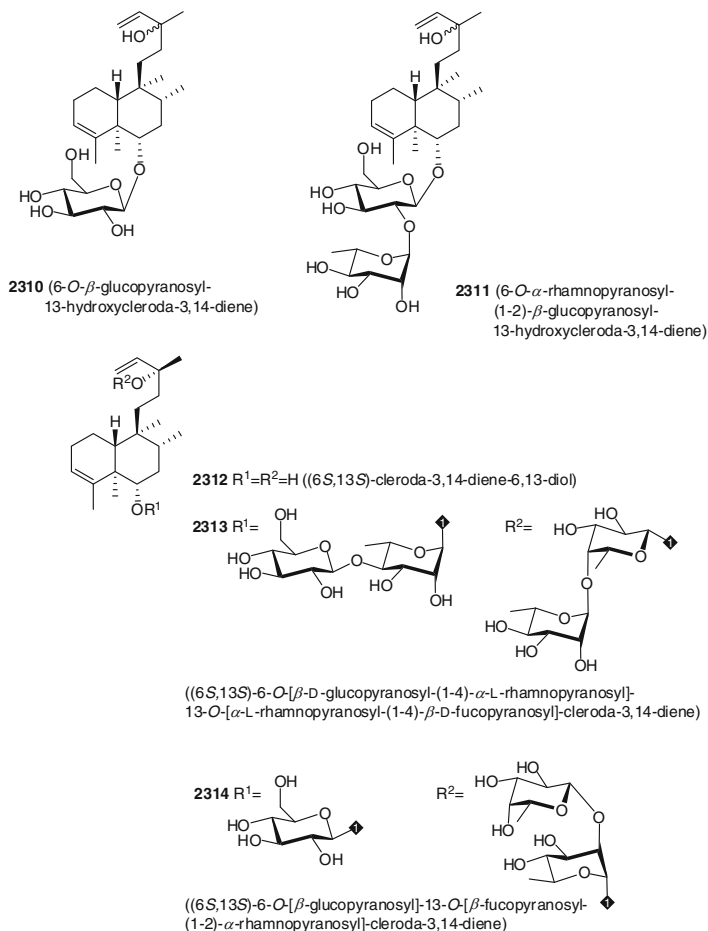


Labdane-type diterpenoids found in the fern, *Gleichenia japonica*

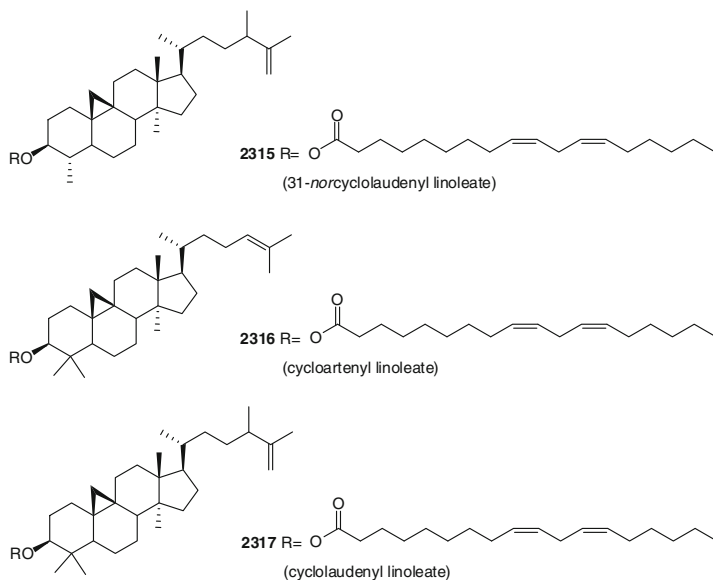
In the case of steroidal components, ferns represent a connection between bryophytes and seed plants. 24-Methylsterol components in the whisk fern (*Psilotum*) and true ferns are similar to seed plants, in which the 24 α -methyl epimer is predominant, while the club mosses (*Lycopodium*, *Selaginella*) are more similar to the bryophytes, with the 24 β -methyl epimer being predominant. The pteridophytes produce exclusively 24 α -ethylsterols, which is characteristic for higher plants but different in many cases from bryophytes, since the latter sometimes produce sterol epimeric mixtures (156).

Lycopodium species are known to produce alkaloids of the lycopodine type. Although the most well-known alkaloid of this class is lycopodine (2318) isolated from *L. flabelliforme* and *L. complanatum*, many other related compounds have been isolated (e.g. 2319, 2320) (86, 503). Alkaloids are characteristic secondary metabolites occurring in higher plants, and, while they have not been detected in

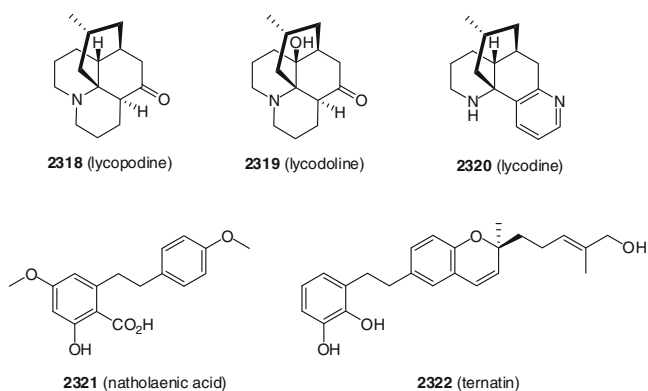
liverworts, prenylated indole derivatives (**2199** and **2200**) have been obtained from the genus *Riccardia* (**40**) and isothiocyanates (**1882** and **1883**) and *S,S*-dimethyl iminodithiocarbonates (**1884** and **1885**) from *Corsinia coriandrina* (**921**). As mentioned in Sect. 9.1, alkaloids have been found in the moss *Fontinalis squamosa* (**704**) and in the hornwort *Anthoceros argestis* (**902**). Despite these reports, the occurrence of nitrogen-containing compounds in bryophytes is fairly rare. When all of this information is taken together, the pteridophytes could have evolved from the bryophytes.



Clerodane-type diterpenoids found in the ferns *Gleichenia japonica* and *Dicranopteris pedata*



Cycloartane-type triterpenoids found in the fern *Polypodium polypodioides*



Lycopodine alkaloids found in the fern *Lycopodium* species and bibenzyl derivatives in the fern *Notholaena* species

There are also a few examples concerning the occurrence of aromatic compounds in liverworts and ferns. The simple thallose liverwort *Hymenophyton flabellatum* elaborates the phenyl butenones, **1852–1857**, and the 4-chromanones, **1849–1851** (77, 900). Compounds **1851** and **1852** have also been isolated from the Japanese fern, *Arachnoides standishii* (803).

The acyclic and cyclic bis-bibenzylys have been considered as aromatic compounds specific to the liverworts. However, perrottetin H (**2206**), previously

detected in the liverwort *Jubula japonica*, has also been isolated from the Japanese fern *Hymenophyllum barbatum* (633). It is also significant that ferns biosynthesize monomeric bibenzyls. Natholaenic acid (2321) and the prenyl bibenzyl ternatin (2322) have been isolated from the ferns *Notholaena dealbata*, *N. limitanea* (942), and *Sceptridium ternatum* (804). Both compounds are structurally very similar to lunularin (1477), lunularic acid (1478), and prenyl bibenzyl (1534), which are characteristic compounds occurring in liverwort species (40).

A summary of the chemical relationships between algae, bryophytes, and pteridophytes is shown in Table 9.1. The main conclusion arising from the data therein is that the liverworts are chemically closely related to algae, especially brown algae, and from this point of view the position of liverworts is supported as the most basal group of extant land plants, as has been shown by molecular analysis, for example by *Qiu* and associates (665). The occurrence of lunularic acid (1478) in algae and liverworts seems to be the most important chemical evidence that the Marchantiophyta are the oldest land plants (663). However, the available chemical data do not support the theory that the first land plants evolved from ancestral charophycean algae or even green algae in general, with two exceptions. The Charophyta as well as simple thalloid liverworts are known to produce flavonoid C-glycosides, which are regarded as phylogenetically primitive. The second similarity is the composition of the polyunsaturated fatty acids in green algae and liverworts. In comparison to red and brown algae, which produce mainly C₂₀–C₂₂ polyunsaturated fatty acids, green algae and liverworts elaborate mainly C₁₆–C₁₈ fatty acids.

Regarding their terpenoid chemistry, liverworts are rather similar to brown algae. Both plant groups produce the same or structurally very similar sesqui- and diterpenoids. Since 80% of the sesqui- and diterpenoids found in liverworts are enantiomers of those found in higher plants (39, 40), it is noteworthy that signs of the specific rotations of compounds isolated from brown algae and liverworts are in many cases the same. Terpenoids are also widespread in red algae, and they are also structurally similar to those found in liverworts. However, a great number of compounds detected in red algae possess carbon-bromine covalent bonds, which do not occur in liverworts. The same situation has been found for green algae constituents, with the exception of the labdane-type diterpenoids isolated from *Ulva* species (151). A second important piece of evidence that the Marchantiophyta are chemically similar to the Phaeophyta is the occurrence of the brown algae pheromones, the dictyopterenes, in the liverwort species *Fossombronina angulosa* and *Chandonanthus hirtellus* (492, 494, 919).

The data presented in Table 9.1 also show that there is a chemical relationship between liverworts and mosses, although their morphology is quite distinct. The most significant similarities are the presence of *ent*-cedranes and dolabellanes in the moss *Plagiomnium acutum* (884), the isolation of a bis-flavonoid (1909) from the liverwort *Chandonanthus hirtellus* subsp. *giganteus* (441), and the occurrence of the acetylenic fatty acids in both plant groups (189, 190). In comparison to mosses, the chemical composition of the hornworts is quite different from the liverworts. On the other hand, there are some similarities between

Table 9.1 Chemical relationships between algae, bryophytes, and pteridophytes

Compound types, major sub- groups, and specific compounds	Algae			Bryophytes			Pteridophytes
	Red	Brown	Green	Liverworts	Mosses	Hornworts	
	Chlorophyta			Charophyta			
Monoterpenoids	+			+	+		
Sesquiterpenoids							
Cuparanes	++ ^a		+ ^a	+	+		+
Cuparane dimers	+ ^a			+			
Chamigranes	+ ^a			+			
Germa cranes		+		+			
Cubebanes		+		+			
Cadinanes		+		+			
Venticadinoxide (= gongylantoxide)				+		+	
Brasilanes	+			+			
Eudesmanes	++ ^a		+ ^a	+			
Oppositanes	+ ^a			+			
Drimanes		+		+			+
Monocyclofarnesanes	+ ^a			+			
Diterpenoids							
Dolabellanes		+		+	+		
Fusicococanes		+		+			
Pimaranes	+ ^a			+	+		
Prenylguaianes		+		+			
Labdanes			+	+			+

(continued)

Table 9.1 (continued)

Compound types, major sub- groups, and specific compounds	Algae		Bryophytes				Pteridophytes
	Red	Brown	Green	Liverworts		Mosses	Hornworts
				Chlorophyta	Charophyta		
Cyathanes					+		+
<i>Triterpenoids and Sterols</i>							
Polypodatetraenes						+	+
Dammaranes						+	+
Serratanes					+	+	+
Cycloartanes				+	+		
Esters with fatty acids	+		+	+	+		+
24 α -Ethylcholesterol (sitosterol)					+	+	+
24 β -Ethylcholesterol (clionosterol)	+	+	+	+	+	+	
24 α -Methylcholesterol				+	+	+	+
24 β -Methylcholesterol (brassicasterol)	+	+	+	+	+	+	+
<i>Fatty acids</i>							
Polyunsaturated C ₂₀ -C ₂₂	++	++	+	+	+	+	+
Polyunsaturated C ₁₆ -C ₁₈	+	+	++	++	++	++	
Acetylenic fatty acids				+	+	+	
<i>Aromatic compounds</i>							
Benzoates					+		
Cinnamic acid derivatives					+		+
Atranorin and atraric acid					+	+	
Long-chain alkyl phenols		+			+		

[illegible]^aHalogenated compounds

hornworts and mosses. The most characteristic feature of both groups of bryophytes is the ability to biosynthesize alkaloids. A wide range of the lycopodine-type alkaloids has been found in the fern allies, *Lycopodium* species. With reference to their alkaloid chemistry, hornworts seem to represent an evolutionary transition between mosses and ferns. However, regarding the occurrence of the triterpenoids in bryophytes and pteridophytes, ferns are rather similar to mosses. The Pteridophyta appear to be at the interface of the phylogenetic transition between bryophytes and angiosperms. This can be explained by their sterol composition, since 24-methylsterol components in the club mosses (*Lycopodium*, *Selaginella*) are more similar to the bryophytes where the 24 β -methyl epimer is dominant, while the whisk fern (*Psilotum*) and true ferns are more similar to seed plants where the 24 α -methyl epimer is dominant (156). There is one more important chemical piece of information, which lends credence to the theory that pteridophytes are derived from the bryophytes. This is the isolation of a bis-bibenzyl compound (**2206**) from the fern *Hymenophyllum barbatum* (633). The occurrence of bis-bibenzyls in ferns is significant, since previously various acyclic and cyclic bis-bibenzyls have been isolated only from the Marchantiophyta and these compounds are recognized as one of the most important chemical indicators of this class (40).

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