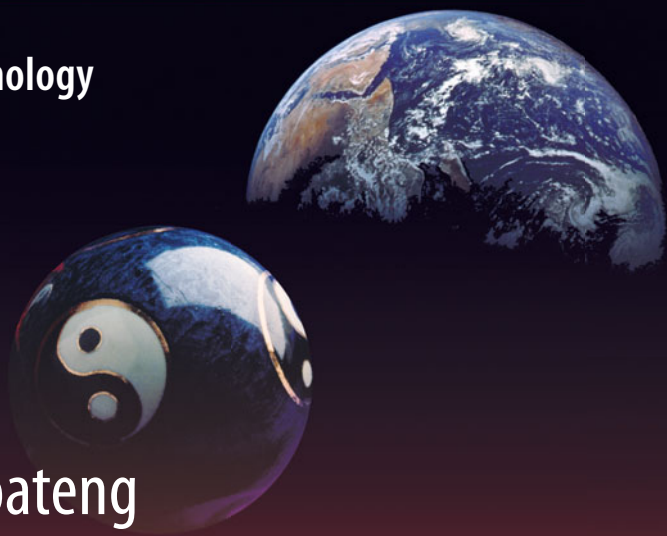


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Keat Teong Lee
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Sustainability of Biofuel Production from Oil Palm Biomass

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Sustainability of Biofuel Production from Oil Palm Biomass

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ISSN 1865-3529 ISSN 1865-3537 (electronic)
ISBN 978-981-4451-69-7 ISBN 978-981-4451-70-3 (eBook)
DOI 10.1007/978-981-4451-70-3
Springer Singapore Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013939336

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Preface

The application of biofuel production systems in solving the global energy crisis has raised controversial issues pertaining to their ecological, thermodynamic, social, economic, political and environmental sustainability. The oil palm industry generates huge amount of biomass every year yet only a small amount is utilized for value-added bioproducts like biofuels, food supplements etc. Sustainability of biofuels from various feedstocks including oil palm biomass are questionable due to many factors such as the heavy use of fossil fuel during production, inefficiency in technological design, generation of large amount of unutilized wastes into the environment etc. However, sustainable energy and resource development should aim for significant reductions on the demand side with greater conservation and improved process efficiency. The major goal of a sustainable production is to effectively utilize resources by minimizing energy and material extraction and throughput per unit of economic output as well as simultaneously improving environmental quality (by minimizing the use of fossil fuel or better still, doing away with them), social well-being of the community while proper policy implementation plans are adhered to.

This book, *Sustainability of Biofuel Production from Oil Palm Biomass* evaluates and discusses the main sustainability challenges encountered during the production of biofuel and other value added bioproducts from oil palm biomass. This book is divided into three main parts with a total of eight chapters.

[Chapter 1](#) gives an overview and comprehensive details on the differences between sustainability and sustainable development with major consideration on biofuels. Biofuels production has various impacts on certain activities such as food production, water quality, biodiversity etc. Thus the choice of raw materials, plantation and harvesting technologies, production process designs, product delivery methods etc. largely determine their sustainability. The dimensions, key issues, initiatives, principles, and criteria for sustainable biofuels production are therefore discussed into details.

Prior to the sustainability assessment of any biofuel production system, there is the need to critically assess technology and the potential of the system to benefit the society. [Chapter 2](#) therefore discusses biofuels in general with great emphasis on biofuel types, production technologies, global production and consumption profiles as well as their market potentials. Biofuels could hold impressive market

potentials in the world today and in the future but their production technologies may be sophisticated and costly which could alter its sustainability for sustainable development.

The palm oil industry in the world generates over 190 million tonnes of wastes in the form of solid and liquid residues. Out of this only about 10 % are utilized commercially for value added bioproducts like biofertilizers. [Chapter 3](#) elaborates on the types of oil palm biomass and their specific characteristics as feedstocks for biofuels production. The potential applications of oil palm biomass for other value added bioproducts are also discussed in [Chap. 3](#).

Among the sources of feedstocks for biofuel production currently available and developed in the world, the oil palm is the prime option which fulfills the sustainability criteria for high productivity, efficiency, competitive price discounts, and above all cost effective. [Chapter 4](#) discusses into details the basic and acceptable production criteria for sustainable oil palm and palm biofuels developments. This chapter highlights on some best management practices involving globally accepted initiatives for sustainable oil palm agriculture, palm oil milling, and refining as well as different production routes to palm biofuels production. Integration of different production routes for various types of palm biofuels through effective utilization of wastes toward sustainable development are also elaborated in this chapter.

[Chapter 5](#) discusses about one of the dimensions of sustainability (environmental sustainability) with case studies of different types of palm biofuels. With the aim of minimizing the dependency on fossil fuels while improving the economic viability and environmental performances of oil palm production for biofuels production, emission control from these systems become invincible. However, with best management practices coupled with stringent adherence to basic environmental sustainability principles, these hurdles may be surmounted. The environmental sustainability dimension of the environmental impact assessment for this chapter is based on life cycle assessment (LCA) for common palm biofuels like biodiesel, bioethanol, biomethanol via BtL route, biogas and bio-electricity (bioenergy) from oil palm biomass.

The production of palm biofuels provides the prospects for new wide economic avenues in terms of job creation, investment opportunities etc. for most people in rural communities in developing countries. [Chapter 6](#) of this book assesses the economic sustainability of different types of palm biofuels and the results are compared to those for fossil fuels. Improvement suggestions for a more economic sustainability of palm biofuels are further elaborated in [Chap. 6](#).

In reality, all production processes proceed with the generation of entropy and destruction of useful energy of resource inputs. In view of this, the second law of thermodynamics can be directly linked with sustainability and sustainable development of production systems. In [Chap. 7](#) of this book, case studies for palm biofuels' (biodiesel, bioethanol, biogas, briquettes etc.) thermodynamic sustainability evaluations are carried out using exergy analysis as the major assessment tool. Thermodynamic sustainability considerations in this chapter include feed-stock (oil palm biomass) production thus giving a better view of the overall

thermodynamic efficiencies of the studied palm biofuel system. Potential causes of inefficiencies and improvement options for sustainable palm biofuels production are also discussed in [Chap. 7](#).

Social sustainability of the palm biofuel industry stresses on the need to produce favorable social and distributional effects like employment, food security, conservation of cultures, equality in sharing between involving parties, technological advancement, and training etc. that would continue to benefit the future generation. The expansion of the oil palm biofuels industry in reaction to the climate change mitigation has necessitated the industry over social, environmental, and political sustainability of palm feedstocks production. Though the production of oil palm biomass and subsequent conversion into biofuels have positive social impacts, some research reports reveal the high rate of unemployment, homelessness and poverty among rural folks who are engaged in oil palm cultivation. [Chapter 8](#) of this book discusses into details the factors that affect the sociopolitical sustainability of palm biofuels and possible improvement suggestions are made.

The authors wish to express their profound gratitude to Universiti Sains Malaysia for their funding through the USM Fellowship and Research University Grant No. 854002.

Contents

Part I Biofuels and Sustainable Development	1
1 Introduction to Sustainability of Biofuels Toward Sustainable Development	3
1.1 The Concepts of Sustainability and Sustainable Development.	3
1.2 Sustainable Production and Consumption	7
1.3 Sustainable Biofuels Production: An Overview	10
1.4 Key Issues of Sustainability and Sustainable Development	11
1.4.1 Sustainability Framework, Principles, Criteria and Indicators.	11
1.4.2 Sustainability Initiatives and Certifications of Biofuels.	15
1.5 Biofuel Sustainability Key Issues	20
1.5.1 Resource Use	21
1.5.2 Land Use Change and Soil Quality	21
1.5.3 Climate Change and Acid Deposition	22
1.5.4 Air Quality.	22
1.5.5 Fresh Water Quality and Quantity.	23
1.5.6 Biodiversity	23
1.5.7 Wastes Production.	23
1.6 Challenges in Adopting Sustainable Biofuel Production Certification	25
1.6.1 Disparities in Biofuel Sustainability Standards for Small and Commercial Scale Producers	25
1.6.2 High Certification Cost	26
1.6.3 Capacity Development.	26
1.6.4 External Support.	27
1.7 Conclusion	27
References	28

2 Biofuels: Production Technologies, Global Profile, and Market Potentials	31
2.1 Introduction	31
2.2 Types of Biofuels and Their Feedstocks: An Overview	32
2.3 Liquid Biofuels for Transportation Purposes, Heat and Power Generation	37
2.3.1 Biodiesel	37
2.3.2 Bioalcohols	49
2.3.3 Other Liquid Biofuels (Bio-oils)	56
2.4 Gaseous Biofuels for Transport, Heat and Power Generation	58
2.4.1 Biogas (Biomethane)	58
2.4.2 Biosynthesis Gas (Bio-syngas)	60
2.4.3 Biohydrogen	61
2.4.4 Biosynthetic Natural Gas (Bio-SNG)	61
2.4.5 Biopropane	62
2.4.6 Global Production and Consumption of Gaseous Biofuels	63
2.5 Solid Biofuels for Heat and Power Generation	64
2.6 Market Barriers of Biofuels	66
2.7 Conclusion	69
References	69
 Part II Biofuels Production from Oil Palm Biomass and Sustainable Development	75
 3 Oil Palm Biomass as Feedstock for Biofuel Production	77
3.1 Introduction	77
3.2 The Oil Palm: History, Botany and Varieties	79
3.2.1 Origin and Distribution	79
3.2.2 Taxonomy and Propagation	80
3.2.3 Botanical Description	82
3.3 Oil Palm Cultivation and Productivity	83
3.4 Biofuel Feedstocks from Oil Palm Biomass: Characterization and Availability	87
3.4.1 First Generation Palm Biofuel Feedstocks	87
3.4.2 Second Generation Palm Biofuel Feedstocks	92
3.5 Future of the Oil Palm Industry as the Sole Source of Oil Palm Biomass	100
3.6 Conclusion	102
References	102

4	Production of Palm Biofuels Toward Sustainable Development . . .	107
4.1	Introduction	107
4.2	Palm Oil Production and Sustainable Development	110
4.2.1	Sustainable Oil Palm Agriculture	110
4.2.2	Palm Oil Milling and Sustainable Development	116
4.3	Sustainable Production and Consumption of Palm Biofuels in Palm Oil Mills	123
4.3.1	Current Technologies for Sustainable Production of Second-Generation Palm Biofuels	125
4.4	Sustainable Practices for Integrated Palm Biofuels and Phytochemicals Production	129
4.5	Sustainable Production of Bio-syngas and Biomethanol from Oil Palm Biomass: A Possible Integration into Palm Biodiesel Production Plant	135
4.6	Integrated Bio-oil, Biohydrogen, and Biogasoline Production from Oil Palm Biomass	136
4.7	Second-Generation Solid Biofuels from Oil Palm Biomass	137
4.8	Best Management Practices for Sustainable Palm Biofuels Production	138
4.9	Global Production and Consumption Statistics of Palm Biofuels	140
4.10	Conclusion	141
	References	142
Part III	Sustainability Assessment of Biofuel Production from Oil Palm Biomass	147
5	Environmental Sustainability Assessment of Biofuel Production from Oil Palm Biomass	149
5.1	Introduction	149
5.2	Environmental Sustainability Assessment: Overview	151
5.3	Environmental Sustainability Assessment via Life Cycle Assessment	153
5.4	Life Cycle Assessment of Biodiesel Production from Oil Palm Biomass	156
5.4.1	LCA Methodology	157
5.4.2	Life Cycle Inventory Analysis	159
5.4.3	Energy Balance for Palm Biodiesel Production System	161
5.4.4	LCA Results and Interpretation for Palm Biodiesel Production	165
5.5	LCA of Combined Heat and Power Generation Plant in Palm Oil Mills	170

5.5.1	System Boundary, Functional Unit and LCI	170
5.5.2	LCA of CHP Generation: Results and Interpretation	171
5.6	Life Cycle Assessment of Palm Bioethanol Production	172
5.6.1	System Boundary, Functional Unit and LCI	172
5.6.2	Palm Bioethanol Production: LCIA Results and Interpretation	174
5.7	LCA of Simultaneous Production of Bio-syngas and Bio-methanol from EFB	176
5.7.1	Goal, System Boundary and LCI	176
5.7.2	LCIA Results and Interpretation of Palm Bio-methanol Production	178
5.8	LCA of Simultaneous Production of Biogas and Bioelectricity from POME	180
5.8.1	Goal, System Boundary and LCI	180
5.8.2	LCA Results and Interpretation: Biogas and Bio-electricity Production from POME	182
5.9	Conclusion	183
	References	184
6	Economic Sustainability Assessment of Biofuels Production from Oil Palm Biomass	189
6.1	Introduction	189
6.2	Economic Sustainability Assessment of Biofuels from Oil Palm Biomass	191
6.2.1	Oil Palm Cultivation and Palm Oil Milling	197
6.2.2	Biodiesel Production from Crude Palm Oil	198
6.2.3	Bioethanol Production from Oil Palm Fronds (OPF) Juice: Cost–Benefit Assessment	203
6.2.4	Economic Sustainability Assessment of Biogas from Palm Oil Mill Effluent (POME)	207
6.3	Economic Impacts of Biofuels from Oil Palm Biomass and Improvement Options	208
6.4	Conclusion	212
	References	212
7	Thermodynamic Sustainability Assessment of Biofuel Production from Oil Palm Biomass	217
7.1	Introduction	217
7.2	Energy, Entropy, and Exergy: Comparative Overview	219
7.3	Components of Exergy	220
7.3.1	Exergy Destruction and Exergy Efficiency	221
7.4	Methodology for Exergy Analysis of Biofuels Production from Oil Palm Biomass	223
7.4.1	Exergy Analysis of Oil Palm Cultivation	225

7.4.2	Exergy Analysis of Palm Oil Milling Processes	228
7.4.3	Exergy Analysis of Biodiesel Production from Crude Palm Oil.	230
7.4.4	Exergy Analysis of Bioethanol Production from Oil Palm Fronds (OPF)	234
7.4.5	Exergy Analysis of an Integrated System for Biomethane and Bioelectricity Production from POME.	239
7.4.6	Exergy Analysis of the Production of Palm Kernel Shells (PKS)-Derived Briquettes	242
7.5	General Improvement Options for Palm Biofuels Production Systems	245
7.6	Conclusion	247
	References	247
8	Social and Policy Issues Affecting the Sustainability of Palm Biofuel Production	253
8.1	Introduction	253
8.2	The Concepts of Social Sustainability	255
8.3	RSPO-RED Schemes for Social Sustainability of Palm Biofuels	257
8.4	Factors Affecting the Social Sustainability of Palm Biofuels Production	259
8.4.1	Employment and Conditions of Service for Workers.	260
8.4.2	Assets Rights and Governance	262
8.4.3	Impacts on Livelihood and Culture	265
8.4.4	Human and Labor Rights	266
8.4.5	Food Security	267
8.5	Regulatory and Policy Initiatives for Sustainable Palm Biofuels Production	268
8.6	Conclusion	273
	References	274
	Appendix A.	279
	Appendix B.	287
	Appendix C.	289
	Appendix D.	293
	Appendix E.	295
	Appendix F: Environmental Impacts Associated with Palm Biofuels Production	297

Appendix G	303
References	307
Glossary	315
Index	319

Abbreviations

ADF	Acid Detergent Fiber
AFU	Average Fuel use per Working Hour (l/h)
APROBI	Association of Biofuel Producers
ARE	Federal Office for Spatial Development
AREA	Operating Area (ha)
ASTM	American Society for Testing and Materials
ASTM-D	American Society for Testing and Materials-Draft
BACP	Biodiversity and Agricultural Commodities Program
BMP	Best Management Practices
BOD	Biological Oxygen Demand (ppm)
BP	By-product Credit (US \$)
BRDi	Biomass Research and Development
BtL	Biomass-to-Liquid Technology
B5	Biodiesel Blend with Petro-diesel (5 % Biodiesel, 95 % Petro-diesel)
B10	Biodiesel Blend with Petro-diesel (10 % Biodiesel, 90 % Petro-diesel)
B100	Biodiesel in Pure Form
CANMET	Canada Center for Mineral and Energy Technology
CC	Capital Cost (\$)
CDIAC	Carbon Dioxide Information Analysis Center
CDM	Clean Development Mechanism
CE	Biodiesel Conversion Efficiency
CERFLOR	Brazilian Program of Forest Certification
CExC	Cumulative Exergy Consumption
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand (ppm)
CPO	Crude Palm Oil
CPKO	Crude Palm Kernel Oil
CPW	Compound Present Worth
CSA	Canadian Standards Association
CSBP	Council on Sustainable Biomass Production
CSPO	Certified Sustainable Palm Oil

DCFRR	Discounted Cash Flow Rate of Return
DEFRA	Department for Environment, Food, and Rural Affairs
DM	Dry Matter
DOE	Department of the Environment
ED	Specific Direct Energy Use (fuel) for Field Operation (MJ/ha)
EEA	Eurostat, European Environment Agency
EFB	Empty Fruit Bunch
EIA	Energy Information Agency
EISA	Energy Independence and Security Act
EN	European Standard
EPFL	Energy Center at Ecole Polytechnique Fédérale de Lausanne
ESMAP	Energy Sector Management Assistance Program
EU	European Union
FAO	Food and Agriculture Organization
FC	Feedstock Cost (US \$)
FFA	Free Fatty Acid
FFB	Fresh Fruit Bunch
FGF	First Generation Feedstocks
FGB	First Generation Biofuels
FP	Feedstock Price (US \$/tonne)
FSC	Forest Stewardship Council
FU	Feedstock Consumption (tonne)
GBEP	Global Bioenergy Partnership
GCF	Co-product Conversion Factor from Feedstock Oil
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GOFBM	Global Oils and Fats Business Magazine
GP	Co-product Price (US \$/kg)
GPI	Genuine Progress Indicator
HYSYS	HYprotech SYStems
IAEA	International Atomic Energy Agency
ICCR	Interfaith Center on Corporate Responsibility
ICGP	Interorganizational Committee on Guidelines and Principles
IEA	International Energy Agency
ILO	International Labour Organization
ISO	International Organization for Standardization
ITA	Investment Tax Allowances
IUCN	International Union for Conservation of Nature
JPOI	Johannesburg Plan of Implementation
LABEN	Labor Energy (MJ/ha)
LABENF	Labor Energy Factor (MJ/h)
LABOR	Number of Working laborers
LCA	Life Cycle Analysis
LCC	Life Cycle Cost (US \$)

LCSP	Lowell Center for Sustainable Production
LPG	Liquefied Petroleum Gas
MC	Maintenance Cost (US \$)
MEMR	Ministry of Energy and Mineral Resources
MPOB	Malaysian Palm Oil Board
MPOWCF	Malaysian Palm Oil Wildlife Conservation Fund
MR	Maintenance Ratio (%)
NBP	National Biofuel Policy
NBPOL	New Britain Palm Oil Limited
NDF	Neutral Detergent Fibre
NEP	National Energy Policy
NGO	Non-Governmental Organizations
NKEA	National Key Economic Areas
NMHC	Nonmethane Hydrocarbons
OC	Operating Cost (US \$)
OECD	Organization for Economic Co-operation and Development
OPF	Oil Palm Frond
OPL	Oil Palm Leaves
OPR	Oil Palm Root
OPT	Oil Palm Trunk
OPW	Oil Palm Wastes
OR	Operating Rate (US \$/tonne)
PC	Annual Biodiesel Production Capacity (Tonne/year)
PD	Petroleum Diesel
PEU	Specific Energy Value per liter of Fuel (MJ/l)
PFAD	Palm Fatty Acid Distillate
PKS	Palm Kernel Shell
PKC	Palm Kernel Cake
POME	Palm Oil Mill Effluent
PORAM	Palm Oil Refiners Association of Malaysia
POTICO	Palm Oil, Timber, Carbon Offset
PP	Payback Period (Year)
PPF	Palm Pressed Fiber
PPO	Pure Plant Oil
PWF	Present Worth Factor
R&D	Research and Development
RBD	Refined, Bleached, and Deodorized
RC	Replacement Cost (US \$)
RED	Renewable Energy Directive
REDD	Reducing Emissions from Deforestation and Forest Degradation
REN21	Renewable Energy Policy Network for the 21st Century
RFA	Renewable Fuels Association
RFS	Renewable Fuel Standard
RMHW	Hamilton Wentworth Regional Council

ROR	Rate of Return
RPKO	Refined Palm Kernel Oil
RPO	Refined Palm Oil
RSB	Roundtable on Sustainable Biofuels
RSP0	Roundtable on Sustainable Palm Oil
RTFO	Renewable Transport Fuels Obligation
RTRS	Roundtable on Responsible Soy
RU	Runs (Number of Application in the Considered Field Operation)
SDC	Swiss Agency for Development and Cooperation
SFI	Sustainable Forest Initiative
SGF	Second Generation Feedstocks
SGB	Second Generation Biofuels
SHF	Separate Hydrolysis and Fermentation
SIRIM	Industrial Research Institute of Malaysia
SNG	Synthetic Natural Gas
SSF	Simultaneous Saccharification and Fermentation
SV	Salvage Value (US \$)
SVO	Straight Vegetable Oil
TAX	Annual Total Tax (US \$/Year)
TBS	Annual Total Biodiesel Sales (US \$/Year)
TGB	Third Generation Biofuels
TGF	Third Generation Feedstocks
TIME	Operating Time (h)
TPC	Annual Total Production Cost (US \$/Year)
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNCSD	United Nations Commission on Sustainable Development
UNEP	United Nations Environment Programme
UNDESA	United Nations Department of Economic and Social Affairs
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
US \$	US Dollar
WCED	World Commission on Environment and Development
WSSD	World Summit on Sustainable Development
WWF	World Wide Fund for Nature
WWI	World Watch Institute

Symbols

C_p	Specific heat capacity (kJ/kmol·K)
d	Deprecation ratio (%)
D^{int}	Internal exergy loss
D^{ext}	External exergy loss

E^{pu}	Produced utilizable exergy
E^{c}	Consumed exergy
$En_{\text{in}}^{\text{net}}$	Net energy into a system (MJ)
$E^{\sim}$	Exergy content
E^{tr}	Transformed exergy
$Ex_{\text{destroyed}}$	Total exergy destroyed, MJ
$Ex_{\text{efficiency}}$	Exergy efficiency
$Ex_{\text{de-activation}}$	Exergy of activation energy used during treatment of wastes (MJ)
$Ex_{\text{emissions}}$	Exergy of wastes (MJ)
Ex_{fossil}	Exergy non-renewable energy resources (MJ)
Ex_{product}	Exergy of the product
Ex_{total}	Total exergy (MJ)
Ex_i	Exergy of i th component (MJ/kg)
$Ex_{\text{ch},i}^0$	Standard chemical exergy of i th component (MJ/kg)
$Ex_{\text{ch},i}$	Chemical exergy of i th component (MJ)
$Ex_{\text{ph},i}$	Physical exergy of i th component (MJ)
$Ex_{\text{ch,mixtures}}$	Exergy of mixtures (MJ)
$Ex_{\text{ch,H}_2\text{O}}^0$	Standard chemical exergy of water (MJ/kg)
$Ex_{\text{kin},i}$	Kinetic Exergy (MJ)
$Ex_{\text{pot},i}$	Potential Exergy (MJ)
h	Specific working hours per run (h/ha)
H	Specific enthalpy (kJ/kg)
H_0	Specific enthalpy at T_0 , p_0 (kJ/kg)
i	year
I	Irreversibility (MJ)
m_i	Mass of i th component (kg)
n	Project life time (year)
N_i	Number of moles of component i
p_i	Pressure of i th component (kPa)
p_0	Reference pressure = 1 atm = 101.3 kPa
q	Quality of joule (work)
Q	Heat flux (J)
r	Interest rate (%)
R	Ideal gas constant = 8.314 J/mol·K
S	Specific entropy (kJ/kgK)
S_0	Specific entropy at T_0 , p_0 (kJ/kgK)
$S_{\text{generation}}$	Entropy generation (MJ/K)
T	Temperature (K)
T_0	Reference temperature = 273.15 K
μ_i	Chemical potential of i th component (kJ/mol ²)
$v_{\text{H}_2\text{O}}$	Mole fraction of water
W_{in}	Net energy into a system
W_{lost}	Lost work (MJ)

ΔG_{fo}	Standard Gibbs free energy of formation (kJ/mol), (kJ/kg)
β	Ratio of chemical exergy to the lower heating value (LHV) or dry organic substances (dimensionless)
λ_i	Mole fraction of i th component

Part I
Biofuels and Sustainable Development

Chapter 1

Introduction to Sustainability of Biofuels Toward Sustainable Development

Abstract Efficient biofuels production that meets the needs of the local, regional, national, and global population are affected by economic, environmental, socio-political, and thermodynamic factors, which have to be managed right in order to achieve sustainable development for the biofuel industry. Biofuels production has various impacts on certain activities such as food production, water quality, biodiversity, etc. Thus, the choice of raw materials, plantation and harvesting technologies, production process designs, product delivery methods, etc., largely determine their sustainability. This chapter therefore elaborates on key issues pertaining to sustainability and sustainable development for the biofuel industry. Some initiatives, which spell out principles and criteria for sustainable biofuels production, are also discussed in this chapter.

Keywords Sustainability • Sustainable development • Sustainable biofuels • Oil palm biomass • Biofuels • Sustainable palm oil • Economic sustainability • Environmental sustainability • Social sustainability

1.1 The Concepts of Sustainability and Sustainable Development

Since time immemorial, the world has not been devoid of challenges pertaining to resource production and consumption due to unprecedented alterations made to the ecosystem by various activities of man. It is either resources are not effectively managed during production or they are not consumed in the right manner resulting in huge burdens on the society. Man's activities have implicated lives on earth in such a way that extra efforts have to be made to provide better goods and services, which are mild to the environment and society at large. The effects of certain agricultural activities such bush burning, deforestation, heavy use of pesticides, and chemical fertilizers, etc., on the ecosystem leave much to be desired.

Biological diversity losses, stratospheric ozone depletion, pollution in all forms (land, water, air, noise, etc.), etc., which are taking dominion over the ecosystem are daunting. All these activities do not stand far from the statement made by Hawken (1993) that “we are drawing down resources that took millions of years to create in order to supplement current consumption.” Unless there evolve a change in the attitudes of man and certain technological actions¹ on resources, the unfriendly touch on the ecosystem would continue and the goal to reduce poverty, diseases and hunger in the near future is likely to be nibbled in the bud. Clean protection of natural resources would therefore require much coordinated efforts in all sectors of the economy (including industries, agricultural sectors, etc.), institutions, etc., to spell out clearly and apply the concept of sustainability, which could further be much easier when there exist friendly policy choices on investment, trade, subsidies, taxation to mention but a few. Through the struggle of achieving peaceful ecosystem for comfortable stay for man, sustainability and sustainable development evolved.

Presently, many countries are enacting policies on sustainability which would eventually lead to sustainable development (Norton and Toman 1997) though it has been difficult in implementing such policies.

The idea of sustainability and sustainable development, which speaks against environmental degradation, economic instability, societal malfunctioning, etc., was dated back to the early 1990s where most countries faced resource management challenges. Though sustainable development comprises many areas all summing up to the shift from “wastes” to “wealth,” it clearly highlights sustainable production and sustainable consumption as the road to sound environment, economy, social progress, and equity all within the limits of the world’s natural resources. In sum, sustainability is the efficient use of goods and services that respond to basic needs as well as improving the lives of people in a society by minimizing the use of natural resources, toxic materials, and emissions from wastes and pollutants over their life cycle so as not to jeopardize the needs of future generations (Norwegian Ministry of the Environment 1994). On the contrary, the utilization of natural resources through such technological processes which generates additional products that are not directly beneficial to man and may result in poor living conditions of man are leading to the road of unsustainability.

Presently, with the hope of hitting the targets of effective resource utilization and management, there have been numerous meetings worldwide aiming at promoting sustainable production and consumption for sustainable development. For instance, in 1992, sustainable development challenges were discussed at the United Nations (UN) Conference on Environment and Development in Rio de Janeiro, which generated into the formulation of 27 major principles for sustainable development in general (UNCED 1992). In 1994, the world’s meeting at the Oslo’s Symposium on sustainable consumption further came up with a clear definition for sustainable

¹ The evolution of advanced technology has brought about the use of environmentally dangerous chemicals like Chlorofluorocarbons (CFC) for the manufacturing certain products etc.

development to help alleviate resource depletion and environmental degradation during a production process. Later, in April 2002, most world leaders signed the Johannesburg Plan of Implementation (JPOI) at the World Summit on Sustainable Development (WSSD), which outlined the abolishment of archaic and inefficient ways of producing and consuming resources in the society (WSSD 2002). An agreement was therefore made in order to encourage and promote the development of a 10-year framework of programs in support of regional and national initiatives to accelerate the shift toward sustainable consumption and production. These initiatives also aimed to promote social and economic development within the carrying capacity of ecosystems by addressing economic growth and environmental degradation through improving efficiency and sustainability in the use of resources with the reduction of wastes. The major areas related to sustainability, which were discussed during the WSSD in Johannesburg, are summarized in Fig. 1.1.

In spite of these important agreements made for the protection of the ecosystem and the efforts in conserving natural resources, the hope of eliminating biodiversity loss by 2010 has not been realized (Global Biodiversity Outlook 3 2010). In view of this, there has been tremendous intensification in researches focusing more on renewable and efficient means of producing and consuming resources in more appropriate ways by using fewer resources and generating less waste pollution leading to sustainable development. “Sustainability and sustainable development”

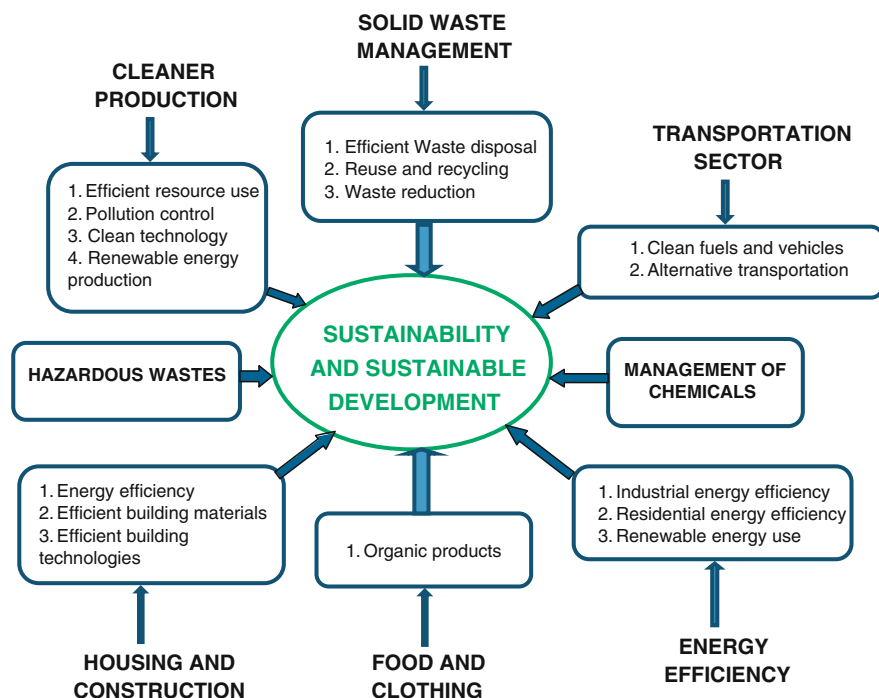


Fig. 1.1 Priority areas of sustainability as described by WSSD (2002)

has been defined in many ways with the context coming to the conclusion that the processes involved in producing a product occur in economical, environmentally benign, and socially sound manner without compromising the needs of the future with the use of natural resources presently.

There are various kinds of definitions for “sustainability” and “sustainable development” all gearing toward the judicious use of resources for better tomorrow taking into account the quality of living in the future. The key aspects of sustainability include effective use of resources, protection of the environment, maintenance of quality and stable economic growth and social improvement that meets the needs of everyone in the community all bouncing back to effective enactment of laws and implementation of those policies to facilitate sustainability and sustainable development.

Though “sustainability” and “sustainable development” are similar in meaning, the effect of one leads to the other. On the road toward sustainable development, sustainability is inevitable. Sustainable development is a long-term goal, which depends greatly on the success to which sustainability brings. Sustainability may not necessarily mean sustainable development because the latter comprises a whole range of developments or positive changes, which are not obtained on silver platter. However, the systematic achievement of sustainability leads gradually to sustainable development. This book focuses on sustainability as a major step in achieving sustainable development for the oil palm biofuel industry.

According to the report by Brundtland (WCED 1987), “sustainable development” is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This definition addresses (1) the prioritization of the vital needs of the people and (2) the barriers created by technological advancement and man’s activities on the ecosystem to achieve safe environment in meeting the needs of today and tomorrow. Hamilton Wentworth Regional Council (RMHW 1992) has also defined “Sustainable development” as “a positive change which requires a coordinated approach to planning and policy making and does not undermine the environmental or social systems on which man depends. However, it involves the participation of the public, which lay much emphasis on the comprehension of the critical relationship between people and their environment and the will to make necessary changes.” The Interfaith Center on Corporate Responsibility (ICCR) considers three main areas (namely, building equitable, productive, and participatory structures) to increase the economic empowerment of the society in the process of achieving sustainable development. In 1995, the UN Commission on Sustainable Development (UNCSD) also proposed the institutional dimension of sustainability though they are mainly regarded as an unquantifiable indicator (IAEA et al. 2005).

Generally, sustainability takes into account the production of a product and the consumption of resources in an efficient way, which leads to sustainable development. Sustainability is focused on reducing resource consumption, saving the environment and improving the lifestyle of man. On the other hand, sustainable development focuses on various individual improvements in sustainable growth of man through the establishment of major infrastructure and amenities.

“Sustainability” has been defined in various ways including:

- *Improving the quality of human life while living within the carrying capacity of supporting eco-system (IUCN/UNEP/WWF 1991).*
- *The principle of taking from the earth only what it can provide indefinitely, thus leaving future generations no less than we have access to ourselves (Friends of the Earth Scotland).*
- *An economic golden rule for the restorative economy: which implies leaving the world better than how you found it by taking exactly what you need, conserving the environment and making profitable amendments to lives on the ecosystem (Paul Hawken 1993).*
- *The principle of extracting natural resources must be at a rate slower than the rate at which they replenish; the rate of producing materials in the ecosystem must not exceed the rate at which those materials degrade within the ecosystem (The Natural Step’s Four System conditions).*
- *Meeting the needs of all humans; being able to do that on a finite planet for generations to come while ensuring some degree of openness and flexibility to adapt to changing circumstances (Bennett and Sturmer 1996).*
- *A balanced interaction between a population and the carrying capacity of an environment such that the population develops to express its full potential without adversely and irreversibly affecting the carrying capacity of the environment upon which it depends (Ben-Eli 2006).*
- *An economic, social and environmental concept which intends to configure civilization and man’s activity in such a way that the needs of the population in the society are met through the preservation of biodiversity and natural ecosystems whilst still planning and acting for the ability to maintain these ideas indefinitely (Wikipedia).*
- *The ability to provide for the needs of the world’s current population by maintaining the surrounding’s ecological processes, functions, biological diversity and productivity over time without damaging the ability of the future generations to provide for (Umpqua Watersheds, Inc.).*

Figure 1.2 summarizes the route from sustainability to sustainable development.

1.2 Sustainable Production and Consumption

Sustainable production may not necessarily mean “no waste,” or “no emission” since a product cannot be made or produced without the generation of by-products. Sustainable production or manufacturing therefore involves the efficient utilization of renewable and safe materials to create cost effective products through safe technologies that do not destroy the environment. In a system like this, situations such as the following exist:

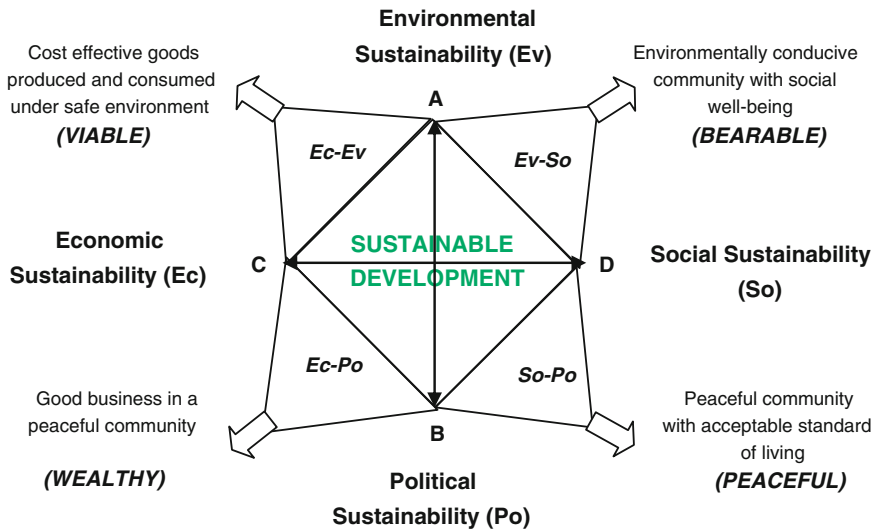


Fig. 1.2 A representation of the route from sustainability to sustainable development A–B: Ev–Po (SECURED) C–D: Ec–So (EQUITABLE)

- Conservation of natural resources (e.g., reuse and recycling of materials) whereby less materials and energy resources are used to produce a product or carry out a service.
- Conservation of energy in material processing whereby there is minimal waste generation, which can further be reused or recycled (e.g., using existing hot water in heating cold water).
- Economically viable processes which result in high quality and cost effective products.
- Effective enactment and implementation of sound policies.
- Healthy and comfortable stay for all workers and consumers in which working conditions of personnel are improved.
- Creation of a nonpolluting environment.

When a production process could be carried out repeatedly with negligible negative environmental effects or impossibly high costs to anyone involved, it can be termed a sustainable system (Sustainable Table). In order to achieve such a conducive system which is referred to as “sustainable production,” the four crucial areas need to be addressed (Fig. 1.2). Goods and services produced sustainably as described by the Lowell Center for Sustainable Production must be biodegradable, durable, safe, and ecologically sound throughout their life cycle whilst utilizing minimal amount of resources including energy (LCSP 1998). Services must be efficiently organized to satisfy man’s needs in order to promote equity. Secondly, the production processes described as sustainable must operate in a way that chemicals, which are toxic to the ecosystem are eliminated and the wastes produced are minimal and recyclable. Technologies must be designed to adhere to the

principles of conservation of energy as well as the optimization of process conditions in sustainable production. Finally, personnel working in a sustainable production environment must be organized in such a way that there is maximum efficiency and creativity whilst their well-being are also secured. Decision making within this system must be open and accepted by the workers. The communities related to any stage of the product's life cycle must be sound economically, socially, environmentally, politically, culturally, and physically. Beder (1996) has also defined sustainable production of a company to be "the indefinite maintenance of the company's activities in which the human welfare is improved through the creation of economically beneficial goods and services."

In the past few decades, the global population has consumed more goods and services than the combined total of all previous generations or productions (Tillard 2000; Millennium Ecosystem Assessment 2005) and this has led to the global economy exceeding the carrying capacity of the planet (Global Footprint Network 2012). The global consumption patterns are said to be unsustainable in some circumstances that are expected to worsen due to increased population yearly. Sustainable consumption defines the consumption or use of goods and services that are socially equitable (i.e., meeting the basic needs man), economically viable, have minimal impacts on the environment and above all improve the lifestyle of man so as not to jeopardize the needs of the future generation (Norwegian Ministry of the Environment 1994). Consumers from all sectors of the economy are the main targets of "sustainable consumption," which is contrary to raw material extraction, preparation and processing into useful products as applied to "sustainable production."

Sustainability is rendered null and void if the supply side (production) is sustainable whilst the demand side (consumption) is unsustainable. Products such as food, fuel, clothing, etc., can be delivered and consumed in efficient ways that could reduce the carrying capacity of the ecosystem. Achieving sustainable consumption of products depends so much on the behavior of the consumers who determine the ways in which they are utilized be it efficient or not. The practice of "double dividend" of sustainable consumption proposed by Jackson (2005) which adopts the trend in simple and altruistic lifestyles of consuming less materials and energy (Brown and Kasser 2005). For instance, a sustainably produced fuel (e.g., biodiesel) can be sustainably consumed in such a way that it would be used only for distances deemed it whilst for short distances bicycles could be used. Figure 1.3 shows some examples of sustainable bioenergy production and consumption supply chains and scenarios.

On the other hand, various types of sustainability have been described by Swiss Agency for Development and Cooperation (SDC) and Federal Office for Spatial Development (ARE) (2004) to be (1) *strong sustainability* which requires that each type of capital or resource cannot substitute each other (2) *weak sustainability* which implies that the different type of capital or resource can substitute each other and (3) *sensible sustainability* also meaning that the total capital or resource is preserved but there exist certain limits for each type of capital or resource below which the stock must not fall. All these types of sustainability depends on how far environmental, economic, and social capital can be substituted for each other.

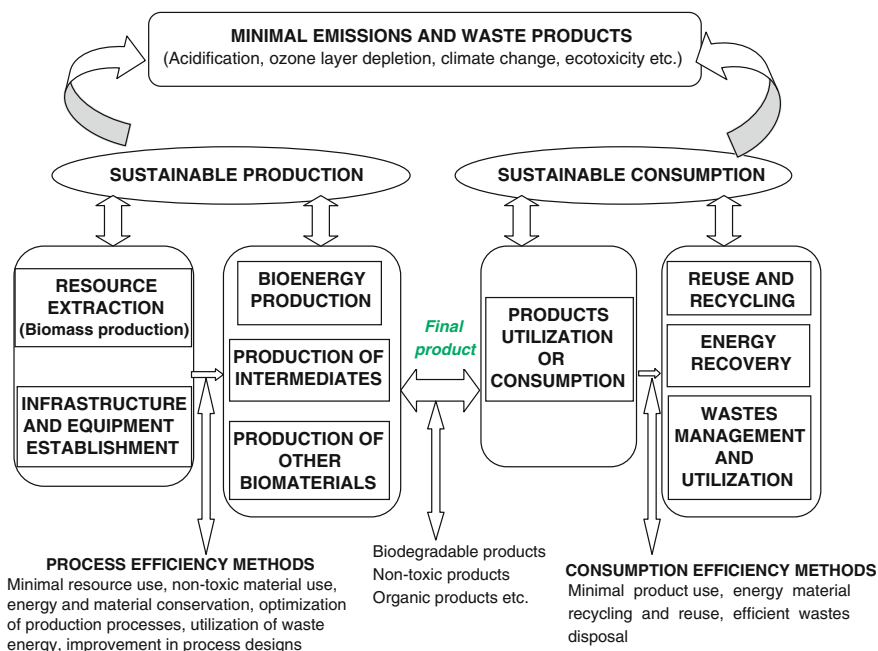


Fig. 1.3 Supply chain for sustainable bioenergy production and consumption

1.3 Sustainable Biofuels Production: An Overview

Energy has been the major driving force of the world's economy, which determines the success of the move toward sustainability and sustainable development. The source of energy used as well as the amount consumed during a process has significant effect on the environment, society and the economy at large. For instance, fossil fuel life cycle from crude production through processing to consumption and wastes disposal is baleful to the society. Thus, the access to green, adequate, and affordable energy services would help impact social well-being of a community's population (IAEA et al. 2005). However, current rise in crude oil prices coupled with its detrimental effects on the environment has increased the growing demand for biofuels. The production of biofuels has therefore gained much attention recently as one of the sustainable ways of energy production. However, notwithstanding the intensive promotion on sustainable production and consumption, most industries in many countries of the world still consume resources in large quantities to produce huge amount of wastes. One such industry is the biofuel industry, which consumes greater amount of fossil fuel, which eventually degrades the environment thus destroying the carbon balance biofuels bring during combustion. Though biofuels are renewable (or green) fuels, their production processes may render them unsustainable owing to inefficient use of resources, environmentally unsafe raw

materials, nonoptimized and poor process designs, etc., which eventually result in costly products. In many developed and developing countries, consumption of resources and the production of products in industries are unsustainable due to the heavy use of nonrenewable resources (e.g., fossil fuel). Again most of these industries like the oil palm industry generate more beneficial yet unutilized wastes like oil palm fronds, palm oil mill effluents, etc., which eventually have negatively impact the society. In order for biofuels production to be sustainable, factors such as costs, environmental, social, and political issues on efficient production as well as the needs of the local, regional, national, and global population must be met. The sustainable production of biofuels dwells so much on the production of the raw materials especially the biomass; hence, the need to address biofuel production sustainability from the feedstock extraction stage.

Biofuels production processes have various impacts on certain activities such as food production, water quality, biodiversity, etc., thus the choice of raw materials, plantation and harvesting technologies, production process design, product delivery methods, etc., largely determines its sustainability. The adoption of green technology is therefore very important in driving the biofuel production systems to the sustainable development envelop.

1.4 Key Issues of Sustainability and Sustainable Development

1.4.1 Sustainability Framework, Principles, Criteria and Indicators

A sustainability framework or standard is a layout of guiding principles, vision and objectives, criteria and indicators of sustainability. It encompasses the directions of attaining desired outcomes, documenting existing situation and strategizing actions and plans to meet a sustainable target. A sustainability framework again outlines specific principles, criteria, and indicators for pursuing the progress towards sustainability and sustainable development.

Sustainability principles cover the general aspirations, which form the sustainability framework by outlining the specific direction of achieving the vision. Sustainability principles for instance, as developed by the the Welsh Assembly Government and the Scottish Executive with support from the Sustainability Development Association (SDC) as agreed upon by the UK government cover five main issues such as: (1) living within environmental limits (2) ensuring a strong, healthy and just society (3) achieving a sustainable economy (4) using sound science responsibly and (5) promoting good governance. Sustainability criteria are also geared toward environmental, social, economic, political, and institutional development. Each criteria contains its own underlining indicators guided by the characteristics of sustainability framework.

On the sustainability standard hierarchy, there are *sustainability criteria* for each principle that are set. These criteria specify the specific aspects of each principle and detail all vital routes and compliance with the sustainability principle.

For a particular standard or framework to operate, indicators which aid in auditing are outlined. These indicators should be quantifiable and verifiable. They are essential for the implementation of the standards because they are actually guiding individual auditors in their assessment work. Indicators can therefore be defined as measured criteria or quantified factors with basic principles under spelt-out framework, which aid in measuring certain factors such as the performance of a nation's economy and also assist in economic policymaking and implementation by translating physical and social sciences' knowledge into manageable units (Reid et al. 1993). Indicators are able to simplify a situation in such a way that it makes sophisticated phenomena quantifiable for information to be communicated in many ways. Indicators are instrumental directors of change within a system. According to McCool and Stankey (2004), indicators may have three main functions as follows:

- Describing the existing conditions and performance of a system.
- Measuring the efficiency activities and policies to move a system toward a more sustainable condition.
- Detecting changes in economic, environmental, social and cultural systems.

However, sustainability indicators are much more comprehensive and consist of diverse structures, requirements and frameworks which help to measure progress toward sustainability (Farrell and Hart 1998). In any business establishment, there are periodic checks on the performance of the company's facilities in order to assess the success of the achievements set as outlined in its goals and objectives. Sustainability indicators are the main tools for carrying out these assessments. There exist various assessment methodologies for economic, social, environmental and political sustainability of a system. An example of an economic sustainability indicator is the genuine progress indicator, which is found to be more advantageous to gross domestic product (GDP) in that it is able to account for costs and benefits of goods and services with little or no economic importance to the society. For instance, GDP and other economic indicators such as gross world product, stock prices only measure consumptions without provisions for utilization of products which also have costs. Another sustainability criteria and indicators which are not often quantifiable are those related to social issues due to the unexistence of consensual accepted societal functional theory (Burgherr 2005). Social indicators basically highlight on births, deaths, income, incidence of diseases, food availability, shelter, population growth, employment, markets, infrastructure, health, security, etc. Life cycle Analysis (LCA) is also a powerful environmental sustainability indicator for evaluating or assessing the ecological sustainability of a system. The thermoeconomic sustainability of a system can also be assessed using various indicators like exergy analysis, exergoeconomic analysis

etc. The regular use of these indicators help move a company toward positive evolutionary stages for better development or transformation through awareness raising and improved dialog with stakeholders.

Sustainability indicators should however address and aim at relevant policy issues, production and consumption efficiencies, validation of logistics, cost effectiveness, and societal progress in all areas within the target. For an achievable sustainability, indicators should be concise and easy to interpret for effective policy making and implementation. Burgherr (2005) described three main characteristics of indicators, which are also applicable to sustainability indicators: (1) Functional: relevant, influential, and comprehensive; (2) Scientific: quantifiable, reproducible, and verifiable; and (3) Pragmatic: manageable, feasible, all-round, and comparable to other indicators in similar area. There are key factors which also distinguish indicators from primary data, parameters or goals, which are called *indicator dimensions*. The use of “renewable energy sources” may not appropriately fit as a sustainability indicator because it cannot be quantified. However, a parameter bearing a unit of measurement such as greenhouse gas savings, percent energy from renewable energy sources, LCA, etc., of production systems over a period of time possibly reflect a true sustainability indicator for biofuel production. According to LCSP (1998), indicator dimensions can be grouped under four main headings namely:

- Unit of measurement such as kilogram which is used in quantifying an indicator.
- Type of measurement whether absolute or adjusted.
- Period of measurement for an indicator.
- Definition of a boundary system (inclusion and exclusion of a particular facility or activity).

The main sustainability indicators described by the LCSP can be subdivided into (1) energy and material use, (2) protection of the natural environment, (3) social justice and community development, (4) economic performance, (5) workers well-being, and (6) clean or green products (LCSP 1998). These indicators serve as guidelines for manufacturing industries in order to ensure the application of green technologies in their practices and produce sustainable products. According to the sustainability framework set by LCSP (1998) for sustainable production, the major sustainability principles within the standards include:

- Design and application of goods and services must be safe and ecologically sound throughout their life cycle.
- Resource conservation must be ensured throughout the production processes.
- Wastes minimization, recycling and reuse of resources must be ensured throughout the production stages.
- There should be minimization of the use of hazardous substances and technologically unsafe practices in order to protect human health and the environment.
- Workplaces must be designed to minimize or eliminate occupational hazards.

- A production process must focus on long term sound economic performance as well as delivering of cost effective products.
- Production practices must be conducted in a way which would enhance the efficiency and creativity of employees.
- The security and well-being of all workers in a production system must be continuously ensured for development of their talents and capacities.
- The communities around workplaces are respected and enhanced health-wise, economically, socially, culturally, physically, etc., to maintain equity and fairness.

The main criteria for biofuel sustainability² however are grouped into economical, social, political, and environmental (ecological) criteria with the main goal of producing and consuming biofuels according to these criteria. Each of these criteria defines its own system conditions and capacity under specific indicator categories with the goal of biofuels sustainability in mind. The production of biofuels begins from feedstock cultivation through to intermediate raw material production and then pretreatment of feedstocks to the real production processes to deliver the targeted biofuel. All these individual processes and stages need to conform to the above-mentioned criteria with specific indicators measuring their sustainability toward sustainable development. The assessment of sustainability becomes more challenging when there is lack of unique and clearly spelt-out goals agreed upon by an acceptable establishment or institution. The impacts of biofuel production on land, energy use, etc., directly affect the impacts on greenhouse gas (GHG) balances compared to other environmental assessment criteria together and this may have great impacts on biofuel sustainability indicator settings as to whether to include these impacts or not. Also, other sustainability indicators may be product-specific and have less impacts, which need critical assessments whether or not to include them in developing biofuel sustainability indicators together. These and many other challenges consequently present a difficult situation in choosing a suitable approach in indicator-settings for biofuel sustainability. In a situation where an indicator is not well selected and applied, the problem of over-aggregation, unnecessary parameters measurements, poor results from false models, incompleteness of tasks etc. are encountered (Meadows 1998).

The first global-level consensus on the issue of sustainability indicators for biofuel production and consumption has been developed by the member countries of the Global Bioenergy Partnership (GBEP) in order for biofuel producers and consumers to know the acceptable management processes in coming up with products in a more sustainable way (Industry news for Bulk Materials Handling 2005). Several other initiatives and certification programs on biofuel sustainability indicators have been proposed by organizations (such as the European standardisation organisation), institutions and nations worldwide. However, depending on such factors as the validity, scope, and applications of these indicators, the various

² Apart from the commonly known criteria for sustainability discussed in this chapter, this book adds thermodynamic sustainability to these criteria and elaborates further in Chap. 7 of this book.

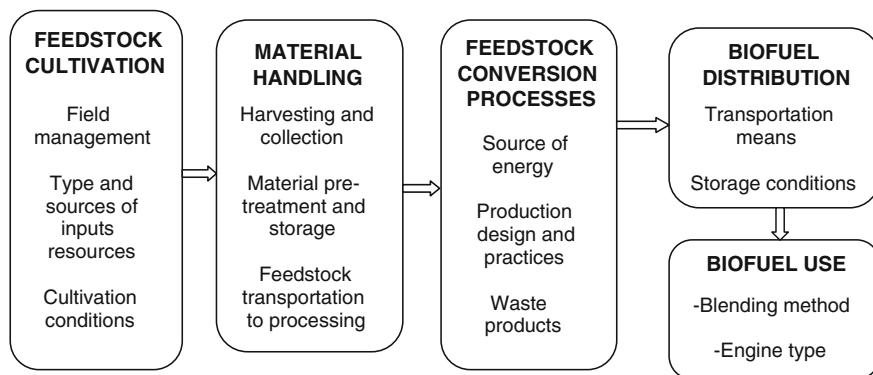


Fig. 1.4 Biofuel sustainability criteria applied to the entire biofuel supply chain

initiatives may vary to suit their conditions on the road toward sustainable biofuel production. Figure 1.4 shows a schematic diagram for the supply chain of main indicators and criteria for sustainable biofuel production.

1.4.2 Sustainability Initiatives and Certifications of Biofuels

Though biofuel subsidies contribute to growth and development of an economy, sustainability issues as well as certifications are the main key issues for stable and sustainable society. Verdonk et al. (2007) have discussed into details some sustainable biofuel certifications elaborating on various case studies. In order to effectively implement sustainability initiatives and certifications, there must be internationally authorized bodies like the UN Framework Convention on Climate Change (UNFCCC) who would decide on how to allocate carbon credits and help implement sustainability standards.

The Roundtable on Sustainable Biofuels (RSB) is an international initiative consolidated by the Energy Center at Ecole Polytechnique Federale de Lausanne (EPFL) in 2007, which aims at bringing together farmers, companies, non-governmental organizations (NGO), governments, and other inter-governmental agencies who are concerned with sustainable production of biofuels. Through multistakeholder processes, the RSB has developed a third-party certification system for biofuels' sustainability standards incorporating environmental, social, economic, and policy principles and criteria. The draft principles and criteria for sustainability of biofuels production worldwide called the "Version Zero" were released by RSB in 2008 whilst the first official draft came out in 2009 (RSB 2008). The main goal of these principles and criteria was to clearly spell out the conceptual scenarios, which people involved in biofuel production would follow.

The cultivation of oil palm for biofuel is a crucial stage in the whole life cycle of oil palm biofuels hence the need for sustainable cultivation and extraction of

palm oil. The Roundtable on Sustainable Palm Oil (RSPO) is also an international multistakeholder organization and certification scheme for sustainable palm oil production, which was initiated in 2004 by various organizations involved in the whole supply chain for palm oil. RSPO has about 400 members³ and affiliates who are involved in sustainable oil palm production. Their main aim was to ensure that palm oil production is economically viable, environmentally safe and socially acceptable. In November 2007, RSPO was able to come up with 8 principles and 39 criteria for sustainable palm oil production, which was subject to review in 2012 (RSPO 2007). Table 1.1 gives some examples of RSPO principles and criteria for sustainable palm oil production. Policy implementation programs as a way of combating unsustainable practices for oil palm and palm oil productions are on course. In Malaysia, for instance, due to increased poverty and social crisis faced by most palm oil smallholders, the new economic policy (NEP) was established to ensure the reduction of poverty and improve on income disparities. With the environmental and social challenges posed by the oil palm industry, the Malaysian government saw the need to address the problem through the 1974 Environmental Quality Act (Braden and Khalid 1993; Vincent 1993), which led to the establishment of a regulatory and licensing body called the Department of the Environment (DOE). A license fee for palm oil mills which varied according to class of mill, location, quantity of wastes generated and pollutants discharged as well as the ambient levels of pollution have been imposed by this body. The method of “discharge more, pay more” has been the implementation option for this policy thus encouraging most of these mills to treat their wastes in an economically and technically feasible manner. Oil mills which failed to comply with these regulations were mandated to shut down their plants, which was a livelihood for peasant oil palm farmers.

Another initiative for sustainable biofuels production is the forum on soy production and consumption stakeholders called the Roundtable on Responsible Soy (RTRS), which aims at developing principles and promoting criteria for the sustainable production of soy. RTRS was initiated in 2005 by the World Wildlife Fund (WWF) and the Swiss supermarket chain COOP with the main focus on introducing “responsible” (sustainable) soy that would meet social, environmental and economic standards of the society (RTRS 2007). The main principles of sustainable soy production as outlined by RTRS include:

- No deforestation of native forest.
- Protection of important areas for nature or community land.
- No use of child or forced labor.
- Safe and regulated use of pesticides.

The Better Sugarcane Initiative (BSI) is another collaboration of sugarcane retailers, investors, traders, producers, NGOs, and other stakeholders with the aim

³ RSPO members and affiliates include oil palm producers, processors and traders, retailers, banks and investors, environmental and social non-governmental organizations (NGOs) etc.

Table 1.1 Summary of RSPO Principles and Criteria for Sustainable Palm oil Production

Principles	Criteria	Indicators
1. Use of appropriate best practices by growers, millers and biofuel producers	1. Appropriate documentation and implementation of operating procedures	Records of measurable results
	2. Production practices must ensure optimum yield whilst the soil's fertility as well as water quality are maintained	Monitoring of soil organic matter content, effluent BOD, water quality assessment etc.
	3. Practices should reduce and control erosion	Assessment of road maintenance programmes etc
	4. Reduced use of pesticides and fertilizers	Monitoring pesticide and fertilizer toxicity etc.
	5. Occupational health and safety plans are effectively implemented	Implementation of health and safety policy; training programmes for workers, etc.
2. Environmental responsibility and conservation of natural resources and biodiversity	1. Identification, adoption and implementation of environmentally sound practices	Environmental impact assessment
	2. Conservation of wildlife	Identification of high conservation value habitat
	3. Reduction of wastes, reuse, recycling and efficient disposal methods	Waste management and disposal plans etc.
	4. Energy efficiency methods and use of renewable energy	Monitoring renewable energy and fossil fuel use
	5. Development and implementation of plans to reduce greenhouse gas emissions	Monitoring of emissions and effluents
	6. Producers must contribute to local sustainable development	Consultations with local communities to assess producers' contribution
3. Responsible development of new plantings	1. Topographical information used for site planning	Soil survey
	2. Social and environmental impact assessments must be made before new planting	Independent impact assessment conducted together with external stakeholders
	3. New plantings must not replace forest land or community land and bush burning must be avoided	Assessment of high conservation value, documented assessment of bush burning areas

(continued)

Table 1.1 (continued)

Principles	Criteria	Indicators
4. Commitment to continuous improvement in key areas of activity	1. Producers must monitor and review their activities periodically	Environmental, social and economic impact assessment
5. Responsible consideration of employees, individuals and communities affected by producers (growers, mills and biofuel producers)	1. Identification, adoption and implementation of production practices and management with positive social impacts	Social impact assessment
	2. Open and transparent communication link between producers and the community	Documented consultation and communication procedures etc.
	3. Implementation of mutually agreed documented systems for dealing with complaints	Assessment of dispute resolution
	4. Working condition of workers must meet an industry's minimum standard and must meet the needs of the workers	Documentation of pay and conditions of work
6. Commitment to long term economic and financial viability	Implementation of management plan to achieve long term economic and financial viability	Documented business or management plan
7. Compliance with applicable laws and regulations	1. There should be compliance with all applicable local, national, ratified international laws and regulations	A system for tracking any changes in laws; documented system with legal requirements
	2. Use of land for oil palm should not diminish the legal rights	Maps showing extent of recognized legal rights
8. Commitment to transparency	1. Adequate information on environmental, social, economic and policy must be provided by producers to stakeholders	Records to request and responses
	2. Management documents must be publicly available	Management documents

Source. RSPO (2007)

of developing internationally acceptable and viable measures for sustainable sugar production processes. One major objective of BSI is to develop a certification system that would help producers, buyers and others involved in sugar and

bioethanol production to obtain products derived from sugarcane that have been produced according to agreed, credible, transparent, and measurable criteria (BSI 2012).

The Nordic Ecolabel (also called the Swan) initiated the Swan labeling of Fuel with the hope of making available a labeling system for licensing biofuels specifically bioethanol, biodiesel, biogas and/mixture of fuels. The framework further elaborates on Banerjee and Solomon (2003), while Monteiro and Rodrigues (2006) discuss eco-certification of agriculture generally. In 2008, it came up with the framework for the production of sustainable biofuel in the Nordic countries (The Nordic Ecolabelling 2008). Some of the Nordic Ecolabelling principles for sustainable biofuel production include:

- Lower emissions during production and consumption.
- Lower risk to people's health or environment impact compared to fossil fuels.
- Documentation of the origin of the raw materials used.

The Netherlands criteria for sustainable biomass production (Cramer et al. 2006) were released in 2006. The framework consists of criteria which lay strong emphasis on biomass for electricity and heat production; and the use of transportation fuel with little emphasis on the utilization of biomass for the production of biochemicals and food. The criteria covered raw materials within and outside the European Union (EU) as well as biofuels such as biodiesel. The main criteria set by the Netherlands for sustainable biomass production covers:

- Greenhouse gas emissions.
- Competition with food and other applications.
- Biodiversity and safe environment.
- Prosperity and social well-being.

The United Kingdom also implemented a Renewable Transport Fuels Obligation (RTFO) in 2008 to provide guidelines for sustainable and renewable fuels. Their sustainability criteria is however limited to the use of biofuels as traffic fuels and the cultivation stages of biofuel feedstock without focus of the production processes transportation activities. The UK criteria were set based in existing framework for sustainable agriculture and forestry.

Other relevant biomass and biofuel certification systems include Forest Stewardship Council (FSC), ISO 14000, Canadian Standards Association (CSA), Sustainable Forest Initiative (SFI), Brazilian Program of Forest Certification (CERFLOR), Global Bioenergy Partnership (GBEP), Biomass Research and Development (BRDi), Council on Sustainable Biomass Production (CSBP), etc., which are all aimed at developing and implementing sustainability frameworks for sustainable biofuels production worldwide. However, the framework developed by these groups are often centered on management practices with limited know-how on sustainable guidelines or practices hence making implementation of such principles too cumbersome.

1.5 Biofuel Sustainability Key Issues

Environmental sustainability framework for biofuels (e.g., biodiesel, bioethanol, biogas, etc.) addresses issues relating to biodiversity, land use, water and soil, conservation, etc. As a first step, framework outlining the principles, criteria and indicators for sustainable biofuel production is set. Normally, biofuel sustainability principles stress on “precaution” other than “paying for emitted pollution.” Globally, all initiatives of sustainable biofuel production take into account “avoidance factor” in terms of environmental pollution and specific criteria and indicators are attached for better implementation.

The economic sustainability is a prerequisite for sustainable production of biomass for energy applications including transportation purposes. Local developmental issues are not only relevant from a social sustainability perspective, but also from the economic sustainability angle. In addition, economic viability of individual operators has to be ensured. Some common economic sustainability indicators include GDP, expenditure components of GDP and personal savings, economic structure, inflation, employment rate, company’s debt and expenditure, consumer expenditure and income, pollution abatement expenditure, infant mortality, life expectancy, etc.

Social biofuel sustainability reflects how the production of biofuels for transportation applications, energy production, etc., affects the development of the community. In particular, social sustainability aims to ensure that the human, land rights, and land use rights are respected. However, it also talks about issues pertaining to labor standards and safety standards within the company and the community at large.

In all circumstances, biofuel production heads toward sustainability with the implementation of supportive policy implementation programs. Political sustainability is a key issue of sustainable production thus has a strong effect on the efficiency of a production system. In the United States, for instance, the goal for sustainable production of biofuels from agricultural resources is reflected in a series of recent U.S. policies such as the Biomass Research and Development Act of 2000, the Energy Policy Act of 2005, the Energy Independence and Security Act (EISA) of 2007, etc. The framework adopted by EISA under the Renewable Fuel Standard (RFS) mandates that by 2022, about 36 billion gallons of biofuels must be produced annually and out of this production capacity, about 16 billion gallons are expected to come from cellulosic feedstocks (Schnepf and Brent 2012). The Food, Conservation, and Energy Act of 2008 (P.L. 110246, 2008 Farm Bill) also includes incentives and programs for accelerating cellulosic feedstock production as well as cellulosic biofuel production and refining. However, sustainability criteria and certifications which are not given into details but only stressing on short-term decisions for the production of cellulosic biofuels could stagnate the progress toward sustainable biofuel production (Robertson et al. 2008).

In general, the move toward sustainability and sustainable development for the biofuel industry cannot be achieved without some basic biofuel sustainability

indicators. The economic, environmental, socio-political, and thermodynamic sustainability of palm biofuels are discussed in the subsequent chapters with references from McBride et al. (2011), RSB (2008) and RSPO (2007).

1.5.1 Resource Use

The major resources utilized within the biofuel industry comprise materials (comprising all kinds of materials excluding fuel and water) and energy resources mostly nonrenewable sources. The supply of raw materials especially feedstock and energy resources for biofuel production must not compete with land for food crop production but must be at competitive prices and sourced from renewable wells in order to reduce adverse impacts of their use on the environment and the society to some acceptable levels. In order to achieve this, wastes could be reused or recycled and process designs could be improved for resource efficiency. For instance, bio-ethanol can be produced from lignocellulosic wastes such as oil palm wastes instead of growing corn and sugarcane for such purposes. Again, green catalysts could be produced from wastes such as oil palm trunks, etc., in order to reduce the burden on the ecosystem caused by toxic chemical use as intermediate materials. In addition, the amount of fertilizer, pesticides, water and energy use during the cultivation of biofuel feedstock must be minimized in order to ensure sustainable production of the biofuels. Organic fertilizers and pesticides could be alternatives whilst rain-water harvesting for irrigation could be encouraged in order to reduce water use from national water line. Water quality and quantity criteria could be measured with indicators such as mineral suspensions, energy use (MJ), mineral concentration (mg/l), etc. Other criteria relevant to ensure efficient resource use within the biofuel industry include reduction in fossil fuels use, increase usage of renewable material and energy resources, reduced consumption of primary and final energy, reduced industrial and commercial sector consumption, reduced fuel prices, etc. These can be measured with thermoeconomic assessment tools and promoted by effective policy implementation plans like subsidies on biofuel prices.

1.5.2 Land Use Change and Soil Quality

The main factor needed to balance the competing demands for the finite quantity of land available for feedstock cultivation is to minimize the loss of forestland in order to preserve biodiversity. Feedstocks like *Jatropha curcas L.* could be cultivated on marginal lands, which are not occupied by settlements. Due to current debates on biofuels competing with food crops for land, one common criterion for sustainable biofuel production is to protect soil as a limited resource for the production of food and other products and as an ecosystem for vital organisms. The common suitable indicators for soil quality include concentrations of organic

matter (total organic carbon content in mg/l), acidity and concentrations (mg/l) of soil nutrients (total extractable phosphorus, total nitrogen, and potassium) in agricultural top soils, bulk density, and concentrations of heavy metals (mg/l) in agricultural top soils. The potential environmental impacts include climate change, humidification, water holding capacity, eutrophication potential, acidification potentials, etc. The selection of suitable crop variety, tillage, fertilizer application, harvesting methods, etc., are the contributing factors to these impacts and must therefore be properly addressed.

1.5.3 Climate Change and Acid Deposition

One key environmental sustainability criteria for biofuel production is the emissions of GHG, which may contribute to global warming and climate change. Fossil fuel use is the main contributor of climate change thus its reduction throughout the life cycle of biofuels are important. Indicators of relevance are GHG radiative forcing rates, global temperature change, carbon dioxide (CO₂) and nitrogen oxides equivalent emissions, road transport emissions of nitrogen oxides, power station emissions measurement of carbon dioxide, etc. All these indicators have gram CO₂ equivalent as their unit of measurement. Fertilizer and pesticides use, tillage, fossil fuel use, management practices, etc., are the main influential factors for these criteria, which lead to climate change potential, ecotoxicity and acidification/eutrophication potentials.

1.5.4 Air Quality

Controlling of air pollution in order to reduce the risks of adverse effects on natural ecosystems, human health, and quality of life during biofuel production is a major sustainability criterion. Indicators for maintenance of air quality during biofuel production include carbon monoxide concentration (mg/l), total particulate matter less than 2.5 μm diameter (PM_{2.5} measured in $\mu\text{g}/\text{m}^3$), total particulate matter less than 10 μm diameter (PM₁₀ measured in $\mu\text{g}/\text{m}^3$), tropospheric ozone concentration ($\mu\text{g}/\text{l}$), volatile organic compound emissions (mg/l), expenditure on air pollution abatement (US\$), etc. Fossil fuel use, biofuels combustion, pesticides and fertilizer applications, management practices, variety of crop selected for production, etc., are the major contributing factors under these sustainability criteria, which eventually result in visibility loss, chronic diseases, acidification/eutrophication potentials, etc.

1.5.5 Fresh Water Quality and Quantity

Biofuel production release large amount of wastewater into the environment. However, in order to maintain sustainable production, water quality and the aquatic environment must be protected. Criteria such as management of the discharge of wastewater are made in order to ensure adequate water resources of sufficient quality and facilitate the recreational use of water where appropriate. Indicators such as chemical and biological oxygen demands (mg/l) of freshwater quality, concentrations of oil and mineral pollutants (mg/l), fertilizer and pesticide concentration (mg/l) in water bodies, expenditure on sewage treatment, water pollution incidents, expenditure on water supply and treatment, etc., are used for measuring the criteria for sustainable biofuel production. Other indicators of this sustainability criteria are nitrate concentration in streams, total suspended solids (mg/l) in streams, total phosphorus concentration (mg/l), water consumption rate ($\text{m}^3/\text{ha}/\text{day}$), peak storm flow (l/s). Factors like amount of wastes generated, pesticides and fertilizer applications, tillage and choice of crop variety affect the sustainability of biofuels production under these criteria. Environmental impacts like eutrophication, benthic habitat degradation by siltation, ecotoxicity, erosion, infiltration, sediment loading, etc., result from these bad management practices.

1.5.6 Biodiversity

During land preparation for feedstock cultivation, bush burning and clearing of forest land destroy wide varieties of wildlife species and habitats thus in order to ensure that commercially exploited species are managed in a sustainable way, indicators such as plant diversity, area of cleared land (ha), habitat fragmentation, mammal or taxa population, etc., are used as measurement tools. These indicators are influenced by the selection of crop varieties, management practices, etc., which could result in ecosystem depletion or biodiversity loss.

1.5.7 Wastes Production

In order to sustainably manage wastes in biofuel industries, there should be minimization of the amount of wastes produced. Efficient waste disposal methods must be used whilst recyclable wastes could be converted into other valuable biomaterials like bio-fertilizers. Article 4 of the revised EU Waste Framework Directive (Directive 2008/98/EC) sets out five steps for dealing with wastes under environmental development called the “waste hierarchy” in the order: prevention, preparation for re-use, recycling, material and energy recovery, and wastes disposal (DEFRA 2012). These criteria have been adopted by the UK government in managing their wastes. Indicators such as anaerobic digestion, composting,

Table 1.2 Sustainability Framework for Biofuel Production

Principles	Criteria	Indicators
Environmental and ecological development		
1. Conservation of biodiversity, ecosystem and immediate production environment	1. Sustainable agriculture	Quantity of Water use, land use, fertilizer and pesticides use; study of impact assessment
	2. Energy and material use	Quantity of Renewable resource use, energy recovery methods; life cycle assessment (LCA)
	3. Protection of natural environment/ biodiversity - Land use change -Water quality -Soil and air quality	Amount and rate of wastes reused and recycled, global warming potential, acidification potential etc. BOD and COD concentrations
2. Using best production technologies to minimize wastes and emissions as well as to conserve water and soil	1. Sustainable industry	Percent energy recovery during production of biofuels, cleaner production assessment (use of renewable energy sources), water and resource intensity, complying to international pollution standards
	2. Protection of natural environment	Rate of water bodies pollution, air pollution etc
3. No or insignificant amount of pollutants released during production	Sustainable residential habitation	Compliance with standardization principles, LCA etc.
4. Ensuring greenhouse gas emission savings of biofuels compared to fossil based fuel	Compliance with regulations in a particular society	1. Genuine methodology for greenhouse gas savings accounting 2. LCA of biofuel production
Economic development		
1. Biofuel production systems should ensure economic profitability and development of the society	Establishment of economic impact assessment (EIA)	1. Accounting and assessment of EIA on the society 2. Assessment of EIA documents
2. Ensuring equitable profit sharing among shareholders, employers and local community of biofuel production systems	1. Assessment of compliance with the national labour law in terms of wages and salary 2. Improving economic conditions of the society as time goes on. 3. Employment generation	Assessment of labour contracts and wages of employees Inspection of macro-economic indicators and statistical documents Number of jobs created

(continued)

Table 1.2 (continued)

Principles	Criteria	Indicators
3. Environmental, Health and safety compliance	1. Economic wellbeing of workers and customers 2. Organizational openness and fairness	Environmental, health and safety compliance cost assessment/auditing Assessing complaints from workers and customers
Socio-political sustainability standards		
1. Biofuel production should help develop a community and promote social justice	1. Sustainable community -Food security -Land availability -Cultural acceptability -Respect for human rights -Acceptable standard of living -Social cohesion	1. Assessment of community benefits from biofuel systems 2. Assessment of company-community partnerships 3. Assessment of the number of employees per unit of product per unit sale
2. Ensuring the wellbeing of workers within the company	1. Good health and safety of workers 2. Incentives for workers 3. Regular training programmes for workers	Rate of accidents and illness Turnover rate or number of working years of workers Assessment from workers
3. Policy implementation of biofuel production standards	1. ISO standardization of biofuel production systems 2. Government incentives and subsidies on biofuel production systems 3. Compliance with law	Periodic assessment of production practices Percentage of products with take-back policies

Source. LCSP (1998)

recovery of energy from wastes engineered landfilling and incineration systems could be used in managing wastes sustainably in the biofuel industry. Typical examples of environmental, social, economic, and political principles, criteria and indicators of biofuel sustainability as described by various initiatives and stakeholders are given in Table 1.2.

1.6 Challenges in Adopting Sustainable Biofuel Production Certification

1.6.1 Disparities in Biofuel Sustainability Standards for Small and Commercial Scale Producers

Achieving biofuel sustainability is a gradual process with lots of challenges for the small-, medium-, and large-scale producers. Among challenge in implementing

biofuel sustainability standards is the limitations of obtaining capital investment, high transaction costs, irregular buyers, high technology costs, etc., especially for the small- and medium-scale producers (Zarrilli 2008; Huertas et al. 2010; Beuningen and Knorringa 2009). For instance, considering RSPO certification, commercial scale producers are better off to adopt the scheme compared to small- and medium-scale oil palm producers. However, there may be exceptions where small-scale private producers are supported by commercial scale ones and in those cases, financial constraints would not be a major concern. This challenge could be eliminated if sustainability indicators and criteria are developed to specifically address the challenges of the small-scale producers. RSPO small holders task force as well as RSB pilot testing for smallholder compliance to sustainability criteria have been in place to address these challenges (RSPO Smallholders Task Force, 2009; RSB 2008) in which about 400 small-scale farmers have been helped in cultivating over 600 ha of *Jatropha curcas* L. for biodiesel production. Government assistance and private partnership among peasant farmers and small-scale biofuel production would help overcome certification barriers in terms of finance and technology by providing incentives.

1.6.2 High Certification Cost

Costs associated with biofuel certification schemes can be grouped into compliance costs, certification process (transaction) cost, and opportunity cost (costs incurred by farmers from missed opportunities) (Bass et al. 2001; Dankers 2003). Compliance costs include the costs from training programs, integrated management techniques, etc. Third-party inspection and administrative costs during certification processes form the transaction costs whilst opportunity costs are incurred when sustainable practices such as minimal use of inorganic fertilizers and pesticides, etc are done. These costs are high for small-scale producers who are large in numbers hence posing a big challenge for their inclusion in certification programs. Donor supports might offset some of these costs by providing the capital for initial certification among smallholders in developing countries though such supports may not be sustainable in the long term (Neilson 2008).

1.6.3 Capacity Development

Another common challenge to sustainable biofuels certification is the lack of sufficient knowledge on green technologies, which poses serious environmental impacts to many companies. Lack of awareness and training programs for producers pose a major problem in implementing sustainability standards (Harris et al. 2001). Producers with low educational background may not be able to effectively

implement certain safety measures and keep records well (Beuningen and Knorringa 2009) thus the need for regular training programs which would guide and facilitate producers' behavior toward more environmentally friendly and other sustainable choices. NGOs and governmental organizations could help finance such trainings so as to achieve the objective of sustainable development. The forest stewardship council (FSC) is a certified small-scale cooperative, which has successfully organized such training programs for knowledge transfer on how to form monitoring and management boards, calculate profit and divide this appropriately to members and how to set rules in a transparent and democratic manner (FSC 2011). Effective capacity development must focus on knowledge transfer that would empower producers to improve the sustainability and profitability of their businesses (Beuningen and Knorringa 2009).

1.6.4 External Support

Apart from NGOs and governmental organizations supporting producers financially, there are other bodies who are directly related to the production chain such as lenders, downstream processors, importers and retailers who need approval before joining certification schemes (Bass Dankers, 2003; Graffham et al., 2007). These bodies provide infrastructure support and help the producers in marketing their products and if these bodies object to certification schemes, the move toward sustainable production would also halt or slow down. For instance, palm oil millers to whom smallholders sell their fruits as well as retailers are in a good position to encourage sustainable practices by providing market access (Vorley et al. 2009). Again, lack of support from the community could massively affect the sustainable production of biofuels.

1.7 Conclusion

It is very necessary for the biofuel industry to adopt and ensure the implementation of the four dimensions of sustainability for sustainable biofuels development. Biofuels sustainability initiatives like the RSPO who are responsible for setting out clear principles and criteria for sustainable biofuels production are currently enforcing the certification on more groups and industries for sustainable feedstocks and biofuels production. Regular checks on best management practices and indicator assessment must be carried out to ensure sustainable biofuels production.

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Chapter 2

Biofuels: Production Technologies, Global Profile, and Market Potentials

Abstract In spite of the benefits associated with the production and consumption of biofuels, there are some crucial debatable issues like high cost, food insecurity, etc., that put them to the negative side. However, biofuels still hold impressive market potentials in the world today though most of their production technologies are sophisticated and costly. Liquid biofuels like bioethanol and biodiesel are commonly produced from feedstocks like corn, rapeseed, soybean, etc., but there are other potential feedstocks, which are more sustainable like palm oil. This chapter discusses the major sources of biofuel feedstocks, types of biofuels, their production technologies, and global market potentials.

Keywords Biofuels market • Palm biofuels • Liquid biofuels • Solid biofuels • Gaseous biofuels • Oil palm biomass • Palm oil • Biofuel production • Transesterification • Pyrolysis • Anaerobic digestion

2.1 Introduction

Presently, fossil fuels such as coal, crude oil, etc., which have been the main sources of energy in the world since the late 1930s, form about 82–86 % of the world's total energy (IEA 2010; Dorian et al. 2006). In 2011, Biofuels contributed about 2 % (about 55 mtoe)¹ of the world's total transportation fuels (EIA 2011) with their associated feedstocks cultivation claiming around 2 % of the world's total arable land (WWI 2006). Over the past decade, the production of biofuels has gained much attention mainly due to the negative impacts of the conventional fuels

¹ A million ton of oil equivalent (mtoe) is approximately equal to 41.87 GJ. Thus, in 2011, biofuels contributed about 2302.85 GJ energy to the world's transportation sector and this is expected to increase to about 750 mtoe in 2050 (EIA 2011).

(especially fossil fuels) on the environment. The most threatening aspect involved with the use of fossil fuels has been their near exhaustion and fluctuations in prices globally. Because biofuels are renewable, they present relatively cheap (i.e., when fossil fuels nearly get exhausted and their prices go high) and secured energy supply in the long term. Sustainable development worldwide cannot be realized with the continuous production and consumption of fossil-based fuels thus the pressing need to promoting sustainable agriculture leading to the sustainable production and consumption of biofuels worldwide.

Biofuel production worldwide has been increasing tremendously in capacity since the year 2000 with major contributing regions and countries being the USA, Brazil, the European Union (EU), China, Malaysia, and India (IEA 2010). Asian countries are forecast to triple their production in the future utilizing feedstocks such as *Jatropha curcas* L., oil palm, etc., that thrive well in tropical climates. Although the cultivation of certain feedstocks and the applications of inefficient technologies for biofuels production may have detrimental effects on the land, water, and biodiversity, one crucial environmental benefit of their consumption has been their insignificant contribution to greenhouse gas (GHG) emissions during combustion. However, the energy and GHG balances need to be effectively intensified in order to generate clean energy throughout their life cycles. This chapter discusses the potential impacts of biofuel types on global market as well as the global production and consumption status. Of late almost all the continents of the world especially North America, the USA, the EU, Asia, and some parts of Africa have prioritized biofuels as transportation fuels and are working hard to offset most of the major drawbacks associated with their production. Though some of these countries (especially the developing ones) have not yet implemented renewable energy regulations, which mandate subsidies and incentives for biofuel producers, the interest in biofuel production is still growing from strength to strength.

2.2 Types of Biofuels and Their Feedstocks: An Overview

Biofuels are either liquid, solid, or gaseous fuels that are derived from the conversion of biomass (organic matter). The energy from biomass is derived from the process of photosynthesis, which utilizes the sun's energy to emit electrons from water molecules. Although fossil fuels have their origin from organic matter, they are not considered biofuels because it takes millions of years (at least 20 million years) for the earth to transform dead organic material into these fossil fuels (which are nonrenewable). Biofuels, on the other hand, are renewable fuels whose feedstocks do not take very long time to grow or ripe for harvest as compared to fossil fuels. However, biofuels are not considered carbon neutral because fossil fuels are used heavily during the cultivation of their feedstocks (e.g., the use of fossil fuel like diesel by irrigation equipment, tractors, etc.) and conversion processes

Table 2.1 Characterization of feedstocks for biofuel production

Feedstock type	Classification	Sources
1. First generation	1. Food (energy) crops	1. Rape seed, soybeans, sunflower seeds, canola, camelina, palm fruits, babassu kernel, coconut kernel, cotton seeds, wheat, barley, sugarcane, cassava, corn/maize
	2. Animal fats	2. Lard, animal intestines, animal parts
2. Second generation	1. Agricultural residues	1. Lignocellulosic materials such as straw, grass, leaves, prunings (such as palm fronds), miscanthus, willow, corn stover, rice husks, palm empty fruit bunches, poplars, eucalyptus, reed canary grass, short-rotation, broadleaved coppice, etc.
	2. Forest residues	2. Lignocellulosic materials like wood chippings, branches, foliage, roots, etc.
	3. Animal and oil wastes	3. Animal manure, tallow, chicken fat, fish oils, waste cooking oil
	4. Nonfood (energy) crops	4. Jatropha seeds, soap nut seeds, mahua seeds (<i>Madhuca indica</i>), indian beech/pongame seeds (<i>Pongamia pinnata</i>), karanj seeds, castor beans, Hemp, monkey cola (<i>Carapa procera</i>), etc.
	5. Biowastes streams	5. Municipal solid wastes (e.g., kitchen/household wastes, construction wood wastes, packaging wastes, etc.), sewage sludge, industrial liquid wastes such as process effluents
3. Third generation (<i>green, brown and red algae</i>)	1. Microalgae	1. Botryococcus, Chlamydomonas, chlorella, spirulina, etc.
	2. Macroalgae (macrophytes or seaweeds)	2. Cladophora, Spirogyra, Hydrodictyon, <i>Barracho spermum</i> , Halimeda, Maiden's Hair, Caulerpa, etc.

into biofuels.² Moreover, as the biofuel industry experiences impressive growth year by year, the production of raw materials also keep creating biodiversity loss as they require land, water, and other resources, which are used for food crop cultivation. Though these and other drawbacks of biofuels exist, they are still environmentally friendly compared to fossil fuels. Biofuels are classified according to the source of feedstock used and the type of fuel produced. Table 2.1 summarizes the common kinds of biomass or feedstocks used for biofuel production.

Biofuels may be in the form of *liquid* such as bioethanol, biodiesel, and pyrolysed oil; *solid* such as firewood, wood pellets, palm kernel shells, sugarcane bagasse, etc; or *gas* such as biogas, syngas, biohydrogen, etc. Solid fuels are not intensely processed (often called *primary biofuels*) and can be directly combusted to release energy for cooking, heating, and electricity generation. Biofuels produced from processed feedstocks (often called *secondary biofuels*) like bioethanol, biodiesel, biogas, charcoal, hydrogen, etc., are mostly used for transportation purposes and high temperature industrial applications. The biomass used as fuel may also be sourced from by-products, co-products, fibers, lignocellulosic materials, which are generated during the production of food products. For instance, black liquor, palm wastes such as oil palm fronds, palm kernel shells, coffee husks, etc., are fuel sources, which are directly combusted to produce energy (in the form of heat and electricity) in many countries of the world.

Depending on the source of feedstock for production, biofuels are classified as first-, second-, and third-generation biofuels (Larson 2008). *First-generation biofuels* (FGB), also called ‘conventional’ biofuels are the type of biofuels,³ which are produced from first-generation feedstocks (FGF) specifically food crops (e.g., sugar, starch, vegetable oil, animal fats, etc.) and have successfully established firm foundations for second- and third-generation biofuels as their technologies and developments are quite simple. The potential impacts of FGB are immensely linked to the efficient cultivation of the feedstocks as they require land, water, fertilizer, and other materials, which may eventually create environmental hazards and above all food insecurity. These and other drawbacks have been current debatable issues concerning the use of FGF for biofuels production in the world.

Biodiesel production from palm oil, for instance, could record significant GHG savings if the cultivation of the oil palm is done on already used land, which needs no intensive bush clearing, and most importantly, fertilizer and other resource use are minimized. Moreover, since the value of biofuels in connection with carbon abatement cost has direct impacts on the GHG emissions and biofuel production costs, there is the need to efficiently manage the various processes involved in biofuels production. This would eventually reduce the abatement cost of using

² Unless all the input resources (both materials and energy) are sourced from renewable sources, biofuels would not be considered carbon neutral though their contributions to GHG emission may be negligible.

³ FGB include biodiesel from rapeseed oil, bioethanol from wheat, biogas from corn etc.

FGB, which is often as high as US\$ 200–800/ton CO₂ avoided⁴ (CBO 2009). Though FGB are found to exhibit a net benefit in terms of greenhouse gas (GHG) emissions reduction and energy balance, they also have several drawbacks which are outlined in Table 2.2.

Second-generation biofuels (SGB) are biofuels produced from nonfood energy crops, agricultural and forest residues. Though currently, only a few SGB production plants are commercialized (because of technologically unproven efficient conversion of SGF into biofuels), they are expected to overtake FGB in terms of energy balance, GHG emissions reduction, competition of land for food and above all high biofuel yield which are significantly higher than those for most FGB. Lignocellulosic materials that are mostly used as feedstocks for bioalcohol production are found in abundance (with annual production of 10–50 billion tons in dry weight) all over the world (Galbe and Zacchi 2002). However, only about 10 % are sustainably utilized for value-added bioproducts with the remaining being burnt and dumped at unauthorized places creating environmental burdens. Meanwhile, these materials often regarded as wastes could generate bioenergy amounting to about 100 EJ per year (Galbe and Zacchi 2002).

Biofuels from lignocellulosic materials are more advantageous to some other nonfood energy crops such as *Jatropha curcas* L. because they need no land for major cultivation, which may require certain practices that could contribute to GHG emissions. Again, almost all the lignocellulosic materials available now are considered wastes thus a sustainable waste management option would turn them into ‘wealth’ (biofuels). In the short term, supporting FGB production with government subsidies as well as mandatory consumption policies that are stringently implemented may not allow the tremendous growth of SGB dominating the world.

Third-generation biofuels (TGB) are also known as algae fuels whose feedstock may either be from algae (macroalgae or microalgae) or other aquatic biomass. TGB are presently developed with much interest due to the high yields of oil generated from the feedstocks as well as the capture of carbon dioxide from the atmosphere during the feedstock cultivation (which do not need much arable land for growth). Biofuels from algae presently accounts for less than 1 % of the global total biofuel production capacity though there are many other advantages associated with their productions and use as compared to FGB and SGB.

Fourth-generation biofuels are biofuels that are produced from genetically modified or engineered energy crops and organisms that are able to extract CO₂ from the atmosphere more than what their fuels release on combustion (Lü et al. 2011). Feedstocks for the production of fourth-generation biofuels are modified in such ways that breaking them down (using functionally engineered enzymes) into biofuels are much easier due to their loose cell wall. Research and developments are underway with these types of biofuels to contribute to sustainable biofuels production.

⁴ The use of biofuels to cut down GHG emissions attracts about US\$ 754, US\$ 275 and US\$ 306/ton of CO₂ for corn ethanol, cellulosic ethanol and biodiesel respectively. Again, a taxpayer in USA who used a gallon of corn ethanol, cellulosic ethanol and biodiesel would obtain a credit of US\$ 1.78, US\$ 3.00 and US\$ 2.55 respectively as a way of substituting fossil fuels (CBO 2009).

Table 2.2 Advantages and disadvantages of biofuel types

Benefits		Biofuel type	Drawbacks
1. First generation	1.	Net benefit in terms of GHG emissions reduction and energy balance	1. Competition with food crops and water resulting stunted economic growth
	2.	Can save up to 50–60 % carbon emissions compared to fossil fuels	2. Higher total production costs (excluding subsidies, etc.) hence expensive to adopt
	3.	Production technologies are simple, efficient, and inexpensive compared to the other biofuel types by feedstock source	3. Destruction of biodiversity as forests and lands are cleared to grow the crops
	4.	Increased biomass yield per hectare of cultivated land	4. Compete with scarce water resources for irrigation in certain areas of the world
2. Second generation	1.	Can save up to 80 % carbon emissions compared to fossil fuels	5. Contribute much to nitrous oxide emissions and have limited GHG reduction potentials
	2.	Positive energy balance	6. Are not energy efficient during their production processes
	3.	Readily available and access to sustainable feedstocks which are mostly regarded as wastes	7. Displacement of small scale farmers
3. Third generation	1.	Noncompetitive with agriculture and water resources	1. High production cost
	2.	High oil yield per hectare (more than 100 times) compared to first and second-generation biofuels	2. Logistics and supply chain challenges e.g., difficulty in feedstock harvesting, storage, transportation, etc.
	3.	Possible production of different kinds of biofuels (e.g., biodiesel and bioethanol)	1. Energy intensive and economically unsustainable technology ^a
	4.	Suitable for use in cold weather due to the presence of high levels of polyunsaturated fats	2. Due to the presence of polyunsaturated fats, algae biofuels (especially biodiesel) are unstable and most often give rise to poor engine performance
	5.	Reduction in carbon emissions during feedstock cultivation	

^a With the current technology for algae biofuels production, their cost ineffectiveness compared to FGB and SGB is a major challenge. An estimated production cost for algae biofuels is more than US\$ 8 per gallon compared to US\$ 4–5/gal FGB and SGB production. (Davis et al. 2001)

There are basically two main process technologies for producing biofuels, namely, biochemical and thermochemical conversion technologies. Thermochemical conversion processes such as combustion, pyrolysis, gasification, torrefaction, co-firing, combined heat and power (CHP) processes, etc., use heat (and sometimes catalysts) to convert the dried biomass into biofuels (Pramanik 2003). These processes are distinguished by their process conditions such as the use of oxygen and the intensity of heat used. Thermochemical processes such as hydro processing, hydrothermal upgrading are also suitable for wet biomass. Biochemical processes, on the other hand, use enzymes to break down the biomass into biofuels. Such processes include anaerobic digestion, fermentation, composting, transesterification, etc. Each of the technologies is elaborated in the subsequent sections.

2.3 Liquid Biofuels for Transportation Purposes, Heat and Power Generation

Liquid biofuels have been one of the most consumed type of biofuels in the world today. Because they can easily blend or totally substitute petroleum diesel (PD) and gasoline (petrol) as transportation fuels without major modifications to engines and fueling systems, they have attracted much attention and investments. Apart from serving as transportation fuels, they are commonly used in heating and electricity production in most parts of the world. Though many kinds of bio-oils are in use, the commonly used types of liquid biofuels are the first-generation ones mostly biodiesel and bioethanol which represent about 15 and 85 % of the current world's production, respectively (OECD-FAO 2011).

2.3.1 Biodiesel

Biodiesel is a dark or golden brown liquid (depending on the type of feedstock) biofuel, which consists of long chain mono-alkyl esters (depending on the type of alcohol used for its synthesis) of fatty acids produced from biomass-based oil or animal fats that can be blended with PD or used alone. Biodiesel is not only produced from the chemical reaction of lipids with alcohols in the presence of catalysts but also as a product from many other thermochemical processes like pyrolysis. Unlike raw vegetable oil, biodiesel can be used in fuel diesel engines in pure form (i.e., 100 % biodiesel, B100) or when blended with PD in slightly modified diesel engines. Biodiesel blends currently used worldwide include B5 (5 % biodiesel, 95 % PD), B10 (10 % biodiesel, 90 % PD), B20 (20 % biodiesel, 80 % PD), B80 (80 % biodiesel, 20 % PD). B100 and other high-level biodiesel blends (from B25 to B95) are not commonly used compared to B5 and B20 because they are expensive, often require special engine modification and are not

commonly covered by subsidies and other policy regulatory incentives. Moreover, high-level blends have lower energy content per liter of biodiesel and can also increase the nitrogen oxides emissions, cause microbial contamination in tanks and often gel in cold temperatures (Levine et al. 2010). American Society for Testing and Materials (ASTM) International specifications (ASTM D975) allows biodiesel blends with PD in concentrations up to 5 % (B5), which is approved for efficient operation in compression ignition engines designed for PD use.

B100 is found to eliminate almost 90 % of air toxins whilst B20 also reduces the air toxins by about 20–40 % (Joshi and Pegg 2007; Marland 2010). Also, the emissions like NO_x and SO₂ can also be reduced by almost 20 % when biodiesel blends are used (Joshi and Pegg 2007; Crutzen et al. 2008). B100 and B20 are also found to reduce CO₂ emissions by more than 75 and 15 %, respectively compared to PD (Balat 2005; Radich 2004).

Comparing biodiesel to PD, biodiesel possesses better lubricating properties, higher flash point (>200 °C compared to that of PD (52–96 °C) and gasoline (–65 °C)), higher density (~0.88 g/cm³ compared to PD at ~0.85 g/cm³) and higher cetane rating (Yoon et al. 2008; Moser 2009). Biodiesel is immiscible with water and has high boiling point (330–357 °C) and low vapor pressure (<1 mmHg) compared to PD (~8 mmHg). The calorific value of biodiesel (36.76–39.34 MJ/kg) is almost 11 % lower than that of PD (45.46 MJ/kg). These encouraging characteristics of biodiesel make them more suitable for use in diesel engines just like PD (Adebayo et al. 2011) without major modifications.

First-generation biodiesel is basically produced from FGF such as rapeseeds, palm fruits, soybeans, etc. There are several debatable issues about first-generation biodiesel because over 95 % of the current biodiesel in use are produced from edible oils that would continue to create food insecurity in the world if alternatives are not sought. However, the present global production capacity of first-generation biodiesel is not sufficient to replace liquid fossil fuels due to scarcity of land for the cultivation of FGF for biodiesel production. The small percentage of crop land used for FGF cultivation has resulted in global imbalance to food supply and demand market as well as negative environmental impacts (Butler 2006). For instance, in the USA, about 11 million tons and 5.3 million tons of vegetable oils and animal fats are produced annually for many purposes including biodiesel production respectively (EIA 2011). On the other hand, the total PD for transportation as well as crude oil for heating purposes in the USA is estimated at 160 million tons (EIA 2011), which is far higher than the biodiesel which could be produced from soybean oil when the entire arable land area is used. This data show a vast gap between PD and biodiesel produced from FGF thus the need for a more secured alternative feedstock for biodiesel production. Second-generation biodiesel are similar to the first-generation biodiesel in characteristics but produced from nonedible crops such as *Jatropha curcas* L., karanj, *Capara procera*, etc. unlike edible crops that are used for first-generation biodiesel.

2.3.1.1 Biodiesel Production Technologies

The sustainability of biodiesel production depends on so many factors which include:

- Feedstock sources (e.g., edible crops, wastes oil, pyrolysis oil from biomass, etc.).
- Feedstock type based on the amount of free fatty acids (FFA) in the feedstock (e.g., animal fat, vegetable oil (either refined or unrefined, etc.)).
- Feedstock pretreatment method (e.g., solvent extraction, mechanical extraction, hydrotreating, etc.).
- Type of catalysis employed during the production processes (e.g., base or acid catalysis).
- Type and source of alcohol and other raw materials used (e.g., bioalcohol, conventional alcohol, hydrogen, etc.).
- Source of energy used (e.g., fossil fuel, renewable energy, etc.).

Generally, all the above-mentioned factors may affect the cost of biodiesel produced. For instance, high free fatty acid (FFA) feedstocks such as animal fat, waste cooking oil,⁵ etc. may result in high processing cost though the feedstock themselves may be cheap (see [Chap. 6](#) for economic sustainability analysis of palm biofuels). About 75–90% of the cost of biodiesel is mostly assigned to the type and amount of resource inputs into its production (Reaney 1997). And therefore the need for better choice of input resources.

There are four main methods of producing biodiesel namely:

- Use of pure or blended vegetable oils directly in diesel engines.
- Catalytic hydrogenation and thermal cracking (pyrolysis) of oils and fats.
- Microemulsion.
- Transesterification reaction.

The direct use of raw or straight vegetable oil (SVO) like peanut oil as fuel in diesel engines have been demonstrated by Rudolf Diesel in 1893 and successfully been applied since then. However, due to some characteristics of these vegetable oils (such as high viscosity which is about 15 % that of PD), the diesel engines may develop problems with time. Again, other disadvantages of using SVO are associated their high cloud points, high surface tension, low cetane number, high flash point, presence of impurities (like phosphatides), susceptibility to the formation of sludge and coke deposits on combustion (Haas 2005). Solutions to these problems may include (1) refining of SVO to remove gums before use as fuels in engines, (2) preheating of SVO to reduce the viscosity before injection, (3) adjusting injection timing and using quality models of compression engines to avoid engine knocking, which may improve its performance than when used in its pure form.

⁵ FFA levels in animal fats, wastes cooking oil, crude vegetable oil and refined vegetable oil are 10–30, 4–40, 5–65 and 0.01–0.5 % respectively (Marchetti et al. 2008; Liu et al. 2007).

However, blending SVO with PD may also improve the fuel's characteristics significantly but in the long term, engine modifications (which is quite expensive) may be required. A couple of researches have reported the good performances of modified (for long-term use) and unmodified (for short-term use) diesel engines that have been ran on pure SVO such as sunflower oil (Rosca and Zugravel [1997](#); Cigizoglu and Ozaklam [1997](#); Schlick et al. [1988](#)), rapeseed oil (Bialkowski et al. [2005](#)), palm oil (Sapvan et al. [1996](#); Prasad [2010](#)), cotton seed oil (Martin and Prithviraj [2011](#)), coconut oil (Machacon et al. [2001](#)), deccan hemp oil (Hebbal et al. [2006](#)), soya bean oil (Schlick et al. [1988](#); Niehaus et al. [1985](#)), linseed oil, castor oil, mahua oil, and neem oil (Prasad [2010](#)), etc. Also, the use of blended SVO/PD in diesel engines have been demonstrated by several other researches (Wang et al. [2006](#); Tadashi [1984](#); Vellguth [1983](#); Barsic and Humke [1981](#)). Martin and Prithviraj ([2011](#)) have reported a remarkable performance of diesel engine with cotton seed oil when preheated to 70 °C and blended with PD at 60 %. However, Murayama ([1984](#)) had previously suggested an increasingly high pre-heating temperature of 200 °C for improved engine performance. In the UK, the EU, and the USA, rapeseed oil, canola oil, and sunflower oil are blended with PD and used in diesel engines for various purposes. Generally, SVO used in diesel engines present acceptable engine performance and emissions for the short term but operational and durability problems may be encountered in the long-term use.

Simultaneous hydrogenation (also called hydrogenolysis, hydrocracking or hydrotreatment) and catalytic cracking of vegetable oils has recently emerged as one of the efficient methods of producing biodiesel, which was developed by the Saskatchewan Research Council under the sponsorship of the Canada Center for Mineral and Energy Technology (CANMET). A feasibility study on this process has been done using 'tall oil' which is a viscous yellow-black odouriferous liquid generated as residue from the production of chemicals (e.g., during the Kraft process of wood pulping from coniferous trees) as a feedstock to produce biodiesel called "SuperCetane". Tall oil may contain 30–50 % FFA, 40–50 % resin acids and 10–30 % unsaponifiables (Cvengroš et al. [1985](#)). Due to high FFA content of tall oil, they are mostly refined before the hydrogenation process into biodiesel. Apart from CANMET, Coll et al. ([2001](#)) have reported the successful transformation of tall oil into biodiesel through the hydrotreatment method.

Hydrogenation of fats and oils is normally carried out in a reactor (operating at 300–500 °C) equipped with stirrer, heating jacket and reflux tunnel (Lappas et al. [2009](#)). Hydrogen gas is injected into the fats and oils at high pressure which then passes through pre-heaters into the catalytic reactor. The product (comprising a straight chain paraffinic hydrocarbons that are free of aromatics, oxygen and sulfur, and have high cetane numbers) is collected, dehydrated, and distilled at atmospheric conditions. Hydrogenation helps prolong the shelf life of the fuel. The deoxygenated liquid fuel produced after hydrocracking of the biomass are reported to be more stable than biodiesel produced from transesterification process, and also, they contain oxygen and double bonds thus suitable for use in cold areas. This

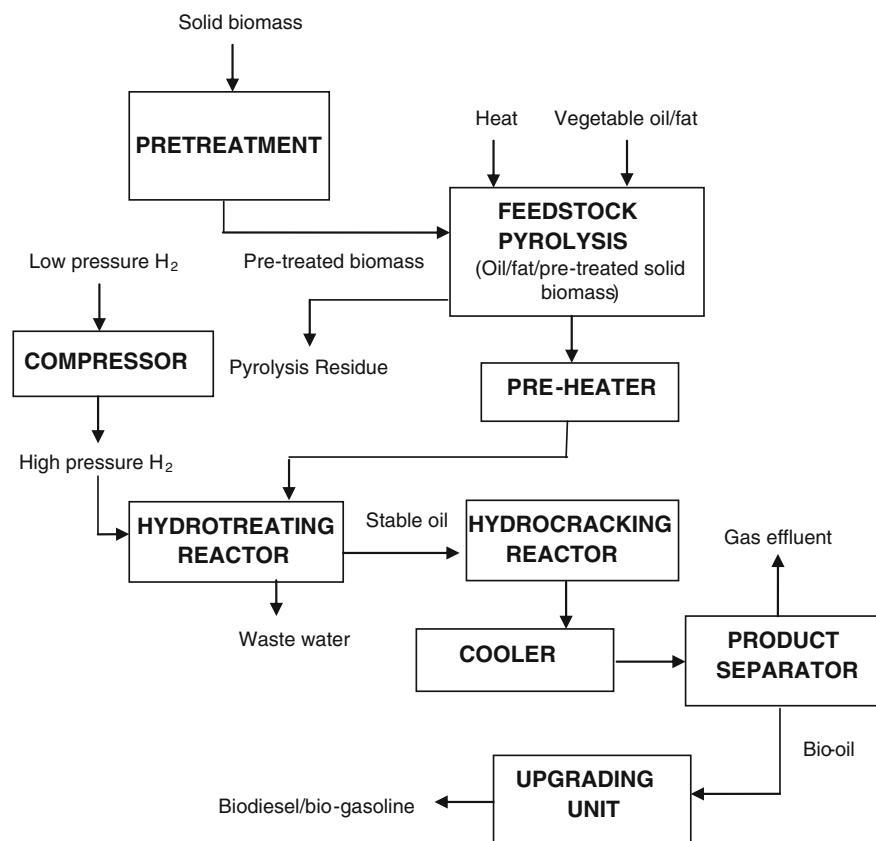


Fig. 2.1 Simplified flow diagram for simultaneous hydrogenation and thermal/catalytic cracking of biomass into bio-oil

method of producing biodiesel and biogasoline has been demonstrated by Nasikin et al. (2009) using palm oil as the feedstock. Figure 2.1 summarizes the production of biodiesel or biogasoline from solid biomass and vegetable oil/animal fat using simultaneous hydrogenation and catalytic/thermal cracking process.

Pyrolysis or thermal/catalytic cracking can also occur independently with hydrogenation of the oils and fats and in this case, no hydrogen is involved. Pyrolysis oils have also been found to possess similar characteristics of PD and can be used in diesel engines though they are not considered complete biodiesel. Pyrolysis oil is highly viscous and basically comprises aliphatic and aromatic oxygenates such as acids, aldehydes, ketones, etc., as well as particulate matter. It has a relatively low energy density of about 19 MJ/kg compared to that of PD (30 MJ/kg) hence may need additional pretreatments before being used as fuels in diesel engines (Solantausta et al. 1994). Thermal/catalytic cracking or pyrolysis is the process of decomposing large molecules into smaller chain compounds by

heating at high temperatures (400–550 °C) and atmospheric pressure (Kersten et al. 2007; Solantausta 2006) anaerobically with or without catalysts.⁶

Zeolite has been reported to possess excellent characteristics as a catalyst for pyrolysis of vegetable oils and fats because of their higher selectivity, thermal stability, ease of separating from the products and the possible regeneration of deactivated catalysts (Neumann and Hicks 2012; Tamunaidu and Bhatia 2007; Williams and Chishti 2000; Chaube 2004).

The products from pyrolysis may include bio-oil, synthetic gas, and char (Boateng et al. 2006). Although thermal cracking of biomass into biodiesel and biogasoline may be costly, in situ upgrading and commercialization may help lower the operational costs thus presenting it an attractive technology in the future. Solantausta et al. (1994) have tested the feasibility of using pyrolysis oil (from sawmill wastes) in a diesel engine with a pilot injection system, which proved to be successful for a short-term use. Other researchers (Billaud et al. 1995; Jones et al. 2009) have also reported the success of using pyrolysis oil blended with PD (whose characteristics were close to those of biodiesel) in diesel engines.

One major problem associated with the direct use of vegetable oils and their blends with PD in diesel engines has been their high viscosity. Microemulsions of oils with alcohols, surfactants, PD, water (mostly as aqueous alcohol), as well as other solvents have been among the common technologies of reducing the viscosity of vegetable oils to be effectively used as fuels in diesel engines without major modifications. However, the problems of carbon deposits, injector needle sticking as well as high viscosity of microemulsions used in diesel engines continue to exist. Microemulsions are thermodynamically stable mixtures of immiscible liquids formed by the dispersion of fluids with optically isotropic microstructures of the fluids with diameters of 150 nm and mostly separated by surfactant films (Fletcher and Morris 1995). Water and alcohols have been the commonly used solvents sometimes blended with vegetable oils for microemulsions and used as fuels in diesel engines. Nguyen et al. (2010) have reported the successful use of water/oil microemulsions blended with PD in the ratio of 40 % in diesel engines without modification. Other studies (Lif and Holmberg 2006; Griffith et al. 1990; Flanagan et al. 2006; Goering et al. 1983) have also tested the possibilities of using water/oil and aqueous alcohol/oil (oils from palm, soybean oil, etc.) microemulsions blended with PD as fuels in diesel engines mostly in the ratio range of 5–95 % microemulsion/PD. These microemulsions have proven to possess good characteristics close to those of PD. Hunter (1996) has reported that improved microemulsion fuels are mostly prepared from about 70–99 % alcohol/fatty acid esters, about 1–30 % alcohol and less than 1 % alkali metal soap. Rao et al. (2012) have also successfully tested the use of microemulsions from alcohol and SVO with PD and rapeseed oil biodiesel blends in a diesel engines. They found out that their characteristics were

⁶ Commonly used catalysts for pyrolysis include silicon dioxide (SiO₂), aluminum oxide (Al₂O₃), zeolites, clay montmorillonite, aluminum chloride, aluminum bromide, ferrous chloride, ferrous bromide etc.

highly comparable to those of PD. Alcohols such as 1-butanol, methanol, and ethanol have been tested to form good microemulsions with vegetable oils, which can be blended with PD and used in diesel engines. All these reports show success for only short-term use without major engine modification. However, long-term use of microemulsions in diesel engines still shows engine coking, injector needle sticking, and carbon deposits thus the need for process improvement in liquid biofuels production for sustainable development.

Presently, the commonest commercial biodiesel production technology is the transesterification reaction (also known as alcoholysis) of the triglyceride of the fatty acid in the oil with alcohol (mostly methanol) catalyzed by a base or acid to produce mono alkyl esters (biodiesel) as main product and glycerin as co-product. This process is able to reduce the viscosity of the oil by a factor of eight; reduce the molecular weight of the oil to one-third that of the original weight and increase the volatility of the oil (Schwab and Bagby 1987). Again, transesterification is a simple process which produces biodiesel whose characteristics are very close to those of PD (compared to those produced from their other methods) and can be directly combusted in diesel engines without modifications with very low carbon deposits (Srivastava and Prasad 2000). In order to achieve sustainability in terms of biodiesel production via transesterification, there are many factors which need to be considered. For instance, the reaction time is dependent on the reaction temperature hence the catalysis may require high/low energy which may alter the sustainability of the biodiesel produced. Figure 2.2 shows the schematic flow diagram of a general transesterification reaction of vegetable oil/fats into biodiesel.

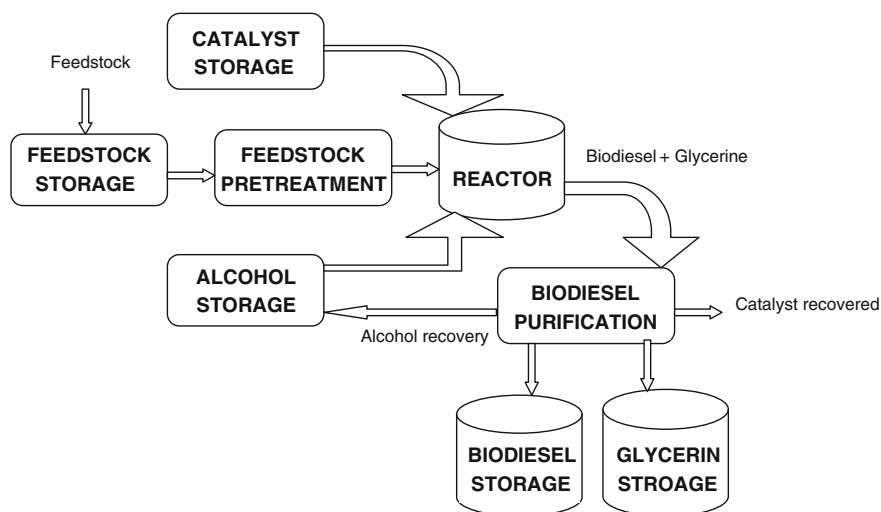


Fig. 2.2 Simplified process flow diagram for transesterification of vegetable oil/fats into biodiesel

Mono alkyl esters can be produced via catalytic, noncatalytic, and supercritical fluid transesterification reactions. Transesterification of oils and fats can be grouped into:

- Acid catalysis
 - Alkaline catalysis
 - Enzymatic catalysis
- } Catalytic Transesterification Methods
- Supercritical fluid transesterification – Non-catalytic transesterification reaction

Transesterification reaction can occur with or without the presence of a catalyst. However, catalysts are mostly used to increase the reaction rate hence shorten the reaction time and increase the biodiesel yield eventually. Catalytic transesterification reaction (acidic, basic, or enzymatic) may be either homogeneous or heterogeneous depending on the type of catalyst used.⁷ Again, these catalysts may be in the form of liquid, solid, or gas with each having its own advantages and disadvantages. After heterogeneous catalysis, the catalyst and biodiesel exist in different physical phases and the possibility of separating them is high. This makes the whole reaction becomes simpler and cost-effective compared to homogeneous catalysis even though its reaction is highly selective (Deshpande et al. 2011). Many researches have investigated into the reaction conditions of transesterification of fats and oils from fish, soybean, rapeseed, sunflower, peanut, palm nuts, linseed, etc. (Saka and Kusdiana 2001; Lang et al. 2001; Mittelbach and Gangl 2001; Diasakou et al. 1998; Joelianingsih et al. 2008) using the various methods of transesterification reactions described above. Table 2.3 summarizes the basic differences between the main types of transesterification methods for biodiesel production.

2.3.1.2 Biodiesel Production and Consumption: Global Profile

Presently, biodiesel is the second most produced and consumed liquid biofuel (though diesel forms about 70 % of road transport fuel) in the world with Germany remaining the leading producer (from rapeseed and imported palm oil) due to the presence and enforcement of biofuel laws and subsidies policies (WWI 2006; EIA 2011). The common feedstocks used for biodiesel production in the world in 2011 are presented in Fig. 2.3.

Biodiesel is currently produced in commercial quantities by many companies like ADM Ölmühle Hamburg in Germany (using rapeseed oil), Diester Industrie in France (a capacity of about 3.5 billion liters of biodiesel using rapeseed and

⁷ Examples of homogeneous catalysts are sulphuric acid (H_2SO_4), hydrochloric acid (HCl), sodium hydroxide (NaOH), potassium hydroxide (KOH) etc. Sulphated zirconium, $\text{K}_2\text{CO}_3/\text{MgO}$ etc. are examples of heterogeneous catalysts used during transesterification reactions.

Table 2.3 Differences between the common types of transesterification methods used in bio-diesel production.

Transesterification method	Pros and Cons
1. Acid catalysis	1. Catalyzed by Bronsted-Lowry acid (mostly sulphonic, sulphuric, hydrochloric and nitric acids) 2. Catalysts are corrosive, hazardous and expensive (yet more active) 3. Slow reaction requiring long time for completion^a 4. High temperature requirement (depending on the type of alcohol) 5. High biodiesel yield (depending on the feedstock type) 6. Mostly accompanied by the formation of carboxylic acids which may reduce the yield and quality of the biodiesel produced. This can be avoided by carrying out the reaction in the absence of water
2. Base catalysis	1. Catalyzed by alkaline catalysts such as alkaline metal alkoxides (e.g., CH₃ONa) and hydroxides (e.g., KOH, NaOH), sodium or potassium carbonates, etc. 2. Catalysts are less corrosive and cheaper (yet less active) compared to acid catalysts 3. Faster reaction hence short time for reaction completion compared to that of acid catalysis 4. Requires low temperature 5. Low yield due to soap formation during the reaction
3. Enzymatic catalysis	1. Mostly catalyzed by free or immobilized lipase 2. Higher cost of enzyme makes the process expensive 3. The insolubility of methanol^b and glycerin in oil inhibit the enzymes hence decreasing the catalytic activity of the transesterification reaction and the operational instability of the enzyme 4. Requires low temperature 5. High biodiesel yield
4. Supercritical Fluid	1. No need for catalyst 2. Technology is simple but cost ineffective due to high pressure and temperature requirements for the reaction to proceed. 3. Shorter reaction time. 4. Higher yield (i.e. more efficient method) compared to the catalytic transesterification methods 5. Easier purification of products 6. Heavy use of fluid for reaction hence increasing raw material cost.

^a Depending on the type of alcohol used, the reaction time may differ (between 6 and 50 h). For instance, for the same amount of alcohol and acid catalysts, transesterification with methanol, ethanol and butanol may take 6–50, 18 and 3 h respectively (Bhatti et al. 2008)

^b Other solvents such as *n*-hexane and petroleum ether have also been reported to exhibit the same problem associated with methanol in enzyme-catalyzed transesterification unlike *n*-butanol, a tertiary alcohol, which is not a substrate for lipases (Shimada et al. 2002; Li et al. 2006)

sunflower oil), GlobalFuel Technologies Corporation (using algae), PetroSun Biofuels Inc. in the USA (a capacity of about 114 million liters of algal biodiesel), Global Green Algae in the USA as well as Biodiesel-Oil-Fujian Zhongde Energy Co. Ltd. in China (a capacity of about 117 million liters of straw oil biodiesel), Gushan Environmental Energy Ltd. in China (a capacity of about 222 million liters

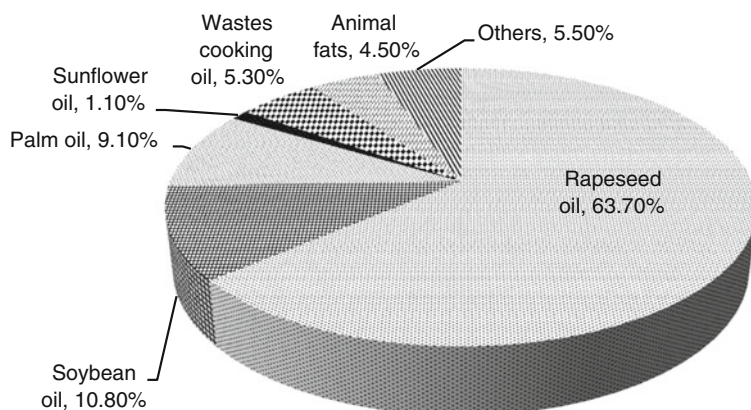


Fig. 2.3 Percent share of feedstocks used for biodiesel production in the world in 2011 ('Others' include non-edible energy crops, bio-oils, etc.)

of biodiesel from used/waste cooking oil), Solazyme in the USA (a capacity of about 114 million liters of producing bio-oil from algae), etc. Algae fuels used as jet fuels and biodiesel are produced by other companies like USA-based Chevron Lummus Global and Aemetis (with a total capacity of about 398 million liters annually in the USA and India). Solazyme Company is set to increase their production capacities and be on the biofuel market by the end of 2013 with a production cost target of US\$ 60–80 per barrel (GigaOM Report 2012). Neste Oil, a BtL production company in Finland is currently using NexBtL process, which is similar to the Fischer–Tropsch process in converting biomass into biodiesel.⁸

A capacity of over 2.1 million tons of BtL production plants are currently in operation in various parts of the world with Singapore, Finland, and the Netherlands accounting for the largest share (about 1.94 million tons) in capacity (Honkanen 2008). Sapphire Energy in the USA is currently one of the biofuel companies in the world with very high production capacity and produces a fourth generation algal bio-oil whose total production capacity is set to hit about 5.7 million liters by 2014 (Honkanen 2008).

In 2008, the global total biodiesel production capacity was 11 million tons which increased to about 21 million tons in 2010 and projected to reach about 84 million tons by 2016, with an annual average growth rate of over 30 % (IEA 2010; EIA 2011). All over the world, biodiesel is consumed at a rate of 3.8 million tons per year and this is also projected to reach about 28 million tons by 2015 (IEA 2010).

These statistics clearly indicate that there is a high possibility of biodiesel contributing as much as 20 % of the world's total capacity of all on-road diesels by 2020. Biodiesel is mainly produced from palm oil in Malaysia, Indonesia, and

⁸ The BtL products (biodiesel and bio-gasoline) produced from palm oil via the NexBTL process are found to have greenhouse gas emissions of about 40–60 % (over its entire life cycle) lower than that for fossil fuel (Hodge 2006).

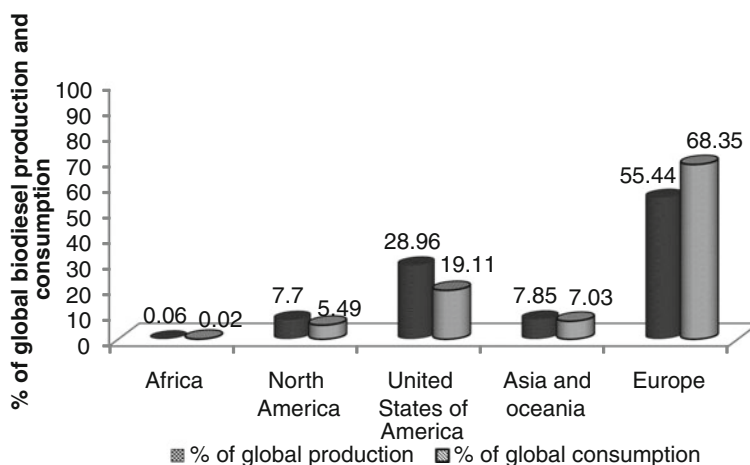


Fig. 2.4 Regional contribution of biodiesel production and consumption to the world's capacity in 2010 (IEA 2010)

Thailand, and other parts of Asia with total palm biodiesel production of about 31.4 million tons annually (Shrestha and Gerpen 2010). As at 2010, the total installed biodiesel production capacity in Malaysia for instance was about 2.7 million tons with active production capacity of about 170,000 tons (MPOB 2010; Lim and Teong 2010). In 2011, about 12 biodiesel production plants (out of the 60 plants with capacity 3.37 million tons which were licensed by the Malaysian government) were actively involved in the production of palm biodiesel contributing about 117,000 tons to the world's capacity (MPOB 2010). In Malaysia, at present, only about 1 % of its palm oil is used to produce biodiesel, whereas Indonesia uses about 9 % of their palm oil for biodiesel production. In 2011, Malaysia exported about 50,000 tons (about 42.7 % of their total production) of biodiesel, which was a drop from about 86,000 tons (about 50.6 % in 2010) bringing in only about RM 266.58 million (MPOB 2010). However, the demand for biodiesel in 2011 was about 200,000 tons. In order to encourage the sustainable production and consumption of biodiesel in Malaysia, the government has provided subsidies of RM 0.05–0.07/l of biodiesel. In the EU, biodiesel production from rapeseed oil was estimated to cost over 3 times higher as that for PD in 2007 (OECD-FAO 2011). In Germany, excise tax exemptions have been driving the demand for biodiesel whilst in the USA, a federal subsidy of US\$ 0.26/l as well as state incentives make the biodiesel market attractive. Figures 2.4 and 2.5 show the regional and global biodiesel production and consumption in 2010, respectively (IEA 2010). From Fig. 2.5, it could be seen that the total biodiesel production and consumption capacities kept increasing from year to year thus the need to adopt sustainability practices in order to achieve the beautiful benefits of biofuels in future.

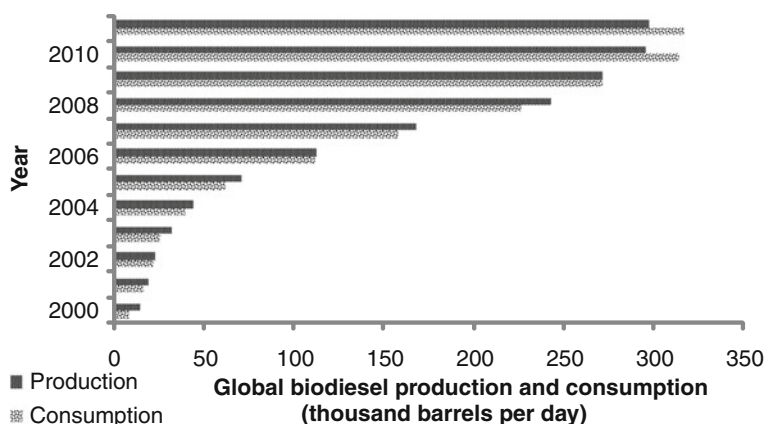


Fig. 2.5 Global biodiesel production and consumption (IEA 2010)

The major feedstock contributors to global biodiesel production over the years have been rapeseed oil (in the EU), soybean oil (in the USA) and palm oil (in Asia) with global contributions of 27, 17, and 10 %, in 2010; respectively (MPOB 2010). *Jatropha* biodiesel has also gained much interest in India and some parts of Asia with minimal contributions presently. The estimated capacity for biodiesel production by 2015 demands large acres of land for feedstock cultivation which would in fact surpass the available global land hence the need for research and developments for second-, third-, and fourth-generation feedstocks for biodiesel production.

Though the EU represents more than half of the global production of biodiesel presently, it is projected that Asian countries like Malaysia and Indonesia may come closer by 2020 as their markets are expanding at faster rates. By the year 2020, it is estimated that biodiesel would represent about 20 % of all on-road diesel fuels used in the world when tax incentives, research and development as well as other sustainability standards are realized in the shortest possible time (IEA 2010). In the EU, in 2011, about 171,000 barrels and 217,000 barrels per day were produced and consumed respectively representing about 6 % of the total on-road diesel fuels in the EU (EIA 2011). By the end of 2005, the EU had achieved their target of 2 % biodiesel contribution to their total on-road diesel fuels. These figures are believed to increase drastically for the next decade if feedstocks become highly available and government subsidies continue to be implemented. In the USA, it is mandated under its Renewable Energy Standard that all cars must run on biodiesel and bioethanol (and their blends with PD) by 2020. Under this law, presently about 3 % of all smaller cars, over 80 % of all commercial trucks and buses run on biodiesel. Apart from the EU and the USA, China, India, and Brazil have also emerged as big markets for biodiesel over the last 5 years (EIA 2011).

2.3.2 Bioalcohols

Bioalcohols are one category of liquid biofuels that are produced from carbohydrate materials. Alcoholic fuels have the chemical formula $C_nH_{2n+1}OH$. Bioalcohols mostly used as fuels include the first four aliphatic alcohols, namely, methanol, ethanol, propanol, and butanol because they can be easily synthesized to be used in engines due to their high octane rating, which increases fuel efficiency and lowers the energy density of fuels compared to gasoline. Bioalcohols have the potential to reduce the emissions of nitrogen oxides (NO_x), carbon dioxide (CO), and nonmethane hydrocarbons (NMHC) by 25–32, 12–24, and 20–22 %, respectively compared to conventional gasoline (CDIAC 2010).

Feedstocks for bioalcohol production consist of mainly cellulose and hemicellulose (hemicellulose and lignin), which are mostly broken down by enzymes, heat or chemicals through various processes. First-generation bioalcohols are produced from sugar and starchy materials such as cassava, cereals (e.g., sugar beet, wheat, etc.), sugarcane, etc. Second-generation bioalcohols (also called cellulosic alcohols) are also produced from cellulosic biomass such as agricultural wastes (e.g., leaves, straw, etc.), forest residues, municipal solid organic wastes, and industrial solid wastes (e.g., sawdust, sugarcane bagasse, etc.). The conversion technologies for lignocellulosic materials into second-generation bioalcohol are sophisticated though the feedstocks are cheaper compared to the FGF. Also the growth of SGF is found to be potentially invasive thus bound to have negative impacts on biodiversity. Nonetheless, bioalcohols produced from SGF can produce greater amount of biomass per hectare of land and most of the feedstocks can grow well on marginal lands where food crops cannot.

2.3.2.1 Bioalcohols Characteristics and Production Technologies

Biomethanol (also called methyl alcohol, methyl hydrate, or wood alcohol) is the lightest, simplest, and less energy-rich bioalcohol that may be produced from synthesis gas (syngas or methane) through gasification, electrolysis or enzymatic conversion of biomass into hydrocarbon rich gas (syngas), which is further converted into biomethanol. Because the technology for producing biomethanol requires large quantities of biomass as feedstock, they are economically feasible when available in large quantities. Biomethanol is found to be the most cost-effective and environmentally friendly liquid biofuel for fuel cell vehicles. The first commercial biomethanol production plant in the world is in operation in Sweden and it produces about 300 tons of biomethanol per day (~ 74 MW) .

Bioethanol is by far the most produced and consumed liquid biofuel in the world mostly obtained from FGF such as corn/maize, beet, sugarcane, wheat, etc. In countries like Brazil, North America, and France, bioethanol (also called ethyl alcohol) is mainly produced from sugarcane, corn/maize, and sugar beet, respec-

tively with Brazil, the USA, and China being the top producing countries (OECD-FAO 2011). Unfortunately, the use of these FGF for bioethanol production directly compete with food for land thus countries like Malaysia and Indonesia are working hard to commercialize second-generation bioethanol production from lignocellulosic materials from solid palm wastes like oil palm fronds. Other disadvantages of bioethanol use may include its ability to be contaminated easily with water compared to gasoline; its corrosiveness; sophisticated production technology (when using lignocellulosic materials as feedstock), etc. Though some studies reveal that bioethanol has lower energy output compared to its energy inputs making them economically unsustainable, Shapouri et al. (2002) and Kim and Dale (2002) have produced a contradictory report. However, apart from bioethanol production from FGF such as corn bringing up the issue of land competition with edible crop production, the technology is simple and cost-effective. On pilot and laboratory scale, bioethanol is commonly produced by the method of separate hydrolysis and fermentation (SHF) using enzymes suitable to completely convert the particular type of feedstock into bioethanol. Hydrolysis is a chemical reaction that converts complex polysaccharides (e.g., starch, cellulose, chitin, glycogen, etc.) in biomass into simple sugars (i.e., monosaccharides) such as glucose (dextrose), galactose, fructose, hexose, xylose, ribose, etc., which is commonly catalyzed by enzymes, acids, and alkaline. Fermentation, on the other hand, converts the simple sugars from the hydrolysis reaction into bioethanol (with carbon dioxide as by-product) with the help of yeast (mostly *Saccharomyces cerevisiae*). Recently, simultaneous saccharification and fermentation (SSF), which employs both the hydrolysis and fermentation of the pretreated feedstock in one reactor, has emerged as a cost-effective method. The utilization of lignocellulosic waste materials may present a more economical way of producing bioethanol commercially if the technology is appropriately developed and accordingly optimized.

Bioethanol has been used extensively as gasoline substitute in most parts of the world. Like biodiesel, bioethanol characteristic performances in gasoline engines are markedly improved by blending with gasoline. Globally, the commonly used bioethanol blends are E10 (10 % bioethanol, 90 % PD), E15 (15 % bioethanol, 85 % PD), and E20 (20 % bioethanol, 80 % PD). Other high level blends such as E85 (85 % bioethanol, 15 % PD), E95 (95 % bioethanol, 5 % PD) have also been used as transportation fuels in the USA, Australia, and Brazil. The high octane rating of these bioethanol blends makes them less prone to knocking (i.e., a rattling or pinging sound that results from premature ignition of the compressed fuel-air) thus improving the energy efficiency of the vehicle's engine for better fuel economy.

Though methanol and ethanol can be produced from fossil fuels or carbon dioxide and hydrogen, they can easily be synthesized from biomass (sugar) by fermentation using enzymes or other chemicals at much cheaper costs relative to those produced from carbon dioxide and hydrogen. The energy contents of bioethanol, biomethanol and gasoline are 21.1, 15.8, and 32.6 MJ/l fuel, respectively (Larson 2008). Bioethanol is less corrosive and less toxic compared to biomethanol and gasoline.

Biobutanol is also another type of bioalcohol, which is not commonly produced due to its complex production technology. Biobutanol is chemically produced from the fermentation (also called acetone-butanol-ethanol (ABE) or solvent fermentation) of biomass using enzymes such as *Clostridium acetobutylicum* and can be used directly in gasoline engines without major modifications. During the ABE fermentation process for biobutanol production, co-products like butyric, propionic and acetic acids are initially formed with the help of the enzyme. Other metabolic activities occur within the fermentation broth which produces butanol, acetone and ethanol (Fond et al. 1985; Qureshi et al. 2002). Biobutanol has high octane rating (85) which is very close to that of gasoline (87) and also has high energy density (29.2 MJ/l) compared to those of bioethanol and biomethanol. Biobutanol, in particular, has its energy density so close to that of gasoline but its production technology is difficult to optimize and still under research and development. However, the high flash point of biobutanol of 35 °C (though a good point for fire safety, it is not suitable for use in cold weather), high toxicity and high emissions of odoriferous substances make them less advantageous compared to biomethanol and bioethanol. Biobutanol can be blended in small quantities with gasoline and used in an unmodified gasoline engines (though some may not be compatible with biobutanol) as its air to fuel mixture ratio (11.2) is close to that of gasoline (14.7).

Presently, there is no vehicle running on 100 % biobutanol apart from few of them which run on its blend (up to 10 % biobutanol) with gasoline (Mansur et al. 2010). Biobutanol is considered accepted for use in diesel engines when its purity is ≥ 99.5 % and contains <0.5 % water and <0.01 % ketones and aldehydes (Mansur et al. 2010). This is indeed difficult specifications to achieve due to the fact that there exists an azeotrope of 94 % purity, which needs to be dealt with during butanol production (Mansur et al. 2010). Because it can produce high voltage compared to the other bioalcohols, they are used as sources of hydrogen in fuel cells, though less preferable, due to the difficult biomass conversion technology into the alcohol.

Biobutanol is mostly produced by fermentation of the biomass with bacteria (often *Clostridium acetobutylicum* or *Clostridium beijerinckii*) to obtain acetone, butanol, and ethanol depending on the process conditions. Unlike bioethanol, biobutanol is resistant to water contamination and safe to handle and transport at high temperatures due to its low vapor pressure compared to gasoline. However, biobutanol on combustion may release more toxic substances or emissions compared to gasoline and presently, the commercial production of biobutanol may not be cost-effective (especially with the distillation process to obtain the biobutanol due to its low concentration in the fermentation broth as a result of product inhibition) compared to that of conventional butanol. Phillips and Humphrey (1983) have investigated the economic analysis of biobutanol recovery through distillation. Their report showed that for efficient energy use in the biobutanol production plant, the concentration of the biobutanol in the fermentation broth must be at least 25 g/l which is in fact difficult to achieve. As reported by Ramey and Yang (2004), biobutanol concentration of 20 g/l, productivity of 4.5 g/l h, and yield of <25 % w/w from glucose have been the best results so far. Other energy recovery methods such as

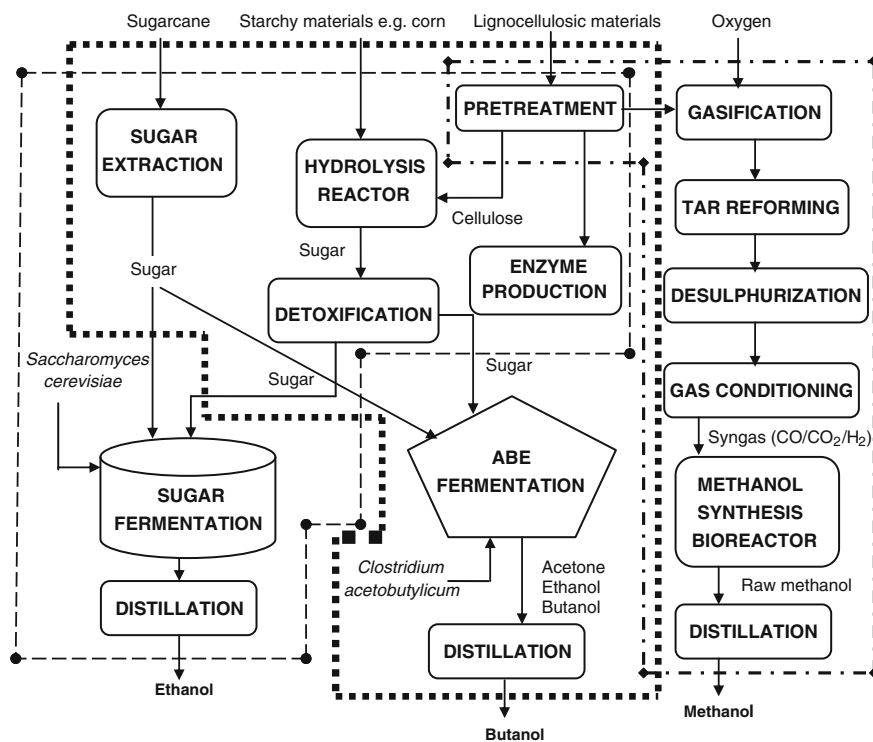


Fig. 2.6 Schematic flow diagram of bioalcohol production from different feedstocks (■ ■ ■ ■ ■, ● — — — ●, ◆ — — — ◆, represent biobutanol, bioethanol, and biomethanol production plants, respectively)

in situ gas stripping, liquid–liquid extraction, reverse osmosis, etc., could be developed and applied for sustainable production (Groot et al. 1992; Chauvatcharin et al. 1998; Ezeji et al. 2003; García et al. 2011). Unlike biomethanol, bioethanol, and biobutanol, biopropanol is not commonly used directly in gasoline engines as fuel but mainly used a solvent. Figure 2.6 describes in brief the process flow of the simultaneous production of types of bioalcohols from biomass.

2.3.2.2 Global Statistics of Bioalcohols Production and Consumption

The greatest volume of liquid biofuels produced and consumed in the world presently is bioethanol produced from wide range of feedstocks with about 80 % sourced from corn and sugarcane together. Presently, bioalcohols are produced from FGF such as corn, barley, oats, rice, wheat, sorghum, sugarcane, etc., mostly in Brazil and the USA. Asia is the leading producer of sugarcane (159 million tons annually) followed by the USA (121 million tons annually) with Brazil being the

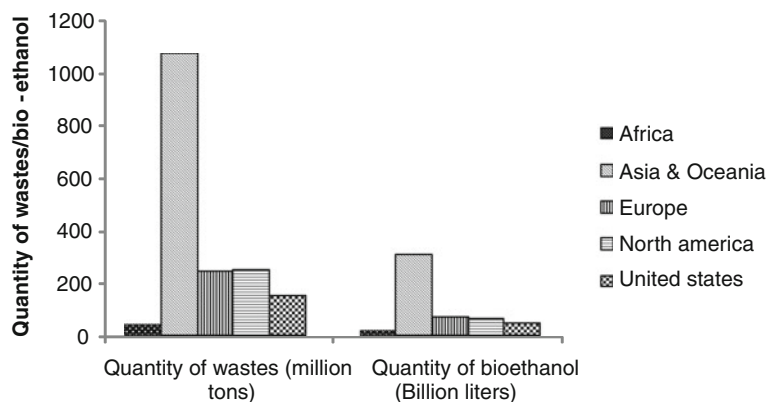


Fig. 2.7 Availability of lignocellulosic wastes for bioethanol production (IEA 2010)

largest single producer accounting for about 98 million tons annually. Out of these production statistics, only about 2 % are used to produce fuel ethanol (OECD-FAO 2011). From 2002 to 2007, the cost of grains in the USA was about 30 % higher due to the production of corn mainly for bioethanol production. By the end of 2007, about 25 % of the total amount of corn produced in the USA was converted to bioethanol (Trostle 2008). All over the world, with the exception of North America, Oceania, and Europe, about 3.3 million tons of sugarcane (which could produce about 1.6 billion liters bioethanol) produced annually go to wastes.

The lignocellulosic wastes obtained after harvesting and pretreatment of these FGF are abundant yet only a few bioethanol production plants that convert these wastes into cellulosic ethanol are commercialized presently due to sophisticated technology involved. All over the world, the major lignocellulosic feedstocks for bioethanol production are abundant (about 1.7 billion tons) especially in Asian countries with the main components being palm wastes, wheat straw, and rice husks (OECD-FAO 2011). In order to achieve bioethanol production sustainability, these wastes referred to as SGF could replace the FGF, which are currently used to produce bioethanol. Figure 2.7 shows the availability of lignocellulosic feedstocks and their potential amount of bioethanol obtained from them in the five regions of the world.

Of all the types of bioalcohols, bioethanol is the most produced in the world presently with North America and the USA dominating and accounting for more than 90 % of the total production capacity. According to the report issued by the Civil Aviation Administration of China (2012), China is the third largest producer of bioethanol, and it is set to reach about 14 billion liters of aviation biofuel by 2020. In 2006, India also contributed about 4 % of the global total bioethanol production and by 2015, they plan to replace about 10–20 % of gasoline by bioethanol. Since 2000, there has been consistent increase in bioethanol production and consumption rate with annual growth of about 6–12 % worldwide (IEA 2010; OECD-FAO 2011).

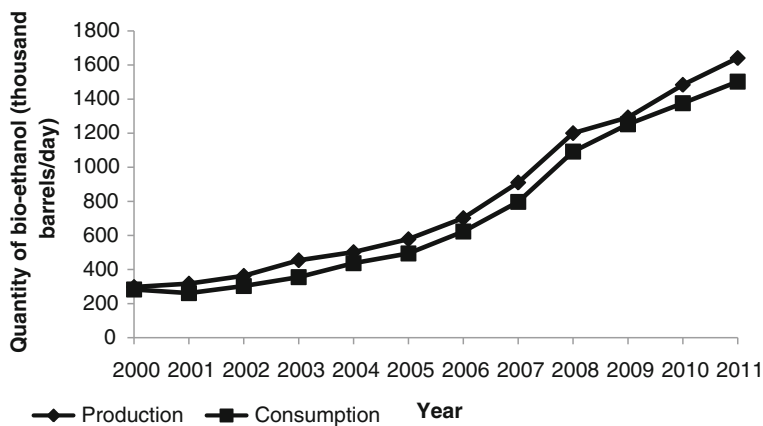


Fig. 2.8 Global bioethanol production and consumption trends from 2000 to 2011

From 2000 to 2007, the world's total bioethanol production had increased three folds due to attractive government incentives in most producing countries. In 2009 and 2010, the global total quantity of bioethanol produced for fuel purposes were about 89 billion liters and 93 billion liters, respectively with consumption capacities of 63 billion liters and 79 billion liters, respectively (OECD-FAO 2011). The consumption rates in Asia and Africa decreased in the year 2009 by about 4 and 80 %, respectively and drastically increased in 2011 by about 13 and 26 %, respectively (OECD-FAO 2011). Figure 2.8 shows the global trend in the production and consumption of bioethanol from the year 2000 to 2011. In 2011, the world recorded a total production of about 99.8 billion liters of bioethanol with about 90 % being consumed as fuel (OECD-FAO 2011; EIA 2011). Presently, the North America holds the greatest share of bioethanol market (about 63 % of the world's bioethanol market) followed by the USA with a share of 31 % of the total world's market (EIA 2011). Although Asia and the Oceania together contribute only about 3 % of the world's market presently, they hold promising future than the EU, which has a share of about 2.7 % (OECD-FAO 2011; EIA 2011). Figure 2.9 shows the regional shares of bioethanol production and consumption in the year 2011.

It was predicted that by the end of the year 2012, Brazil and the USA would have increased their bioethanol production capacity to about 19 million liters (about 20 % their current production) and 30 million liters (about 43 % their current production), respectively (EIA 2011). These regions hope to expand their production, consumption, and market capacities by the year 2020. Globally, whilst the cost of production of a liter of bioethanol is about US\$ 0.22 and US\$ 0.30 in Brazil and the USA, respectively, it is sold at about US\$ 0.53 on the international market (RFA 2010). The difference in prices is as a result of the type of feedstock used. Brazil uses sugarcane, which does not need any pretreatment whilst the USA uses corn which needs some hydrolysis before further fermentation into

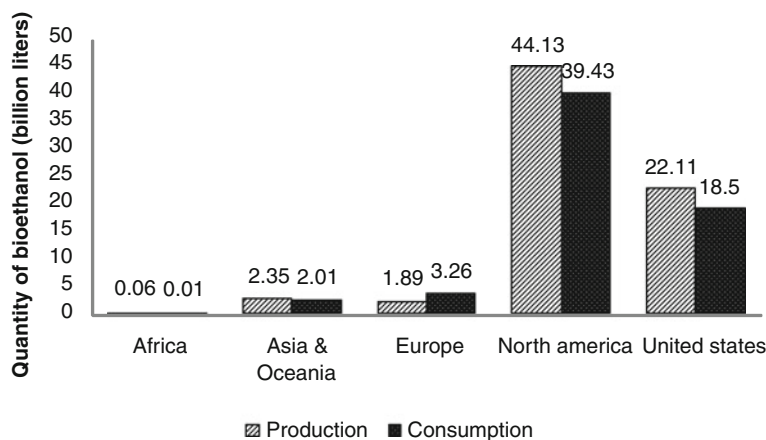


Fig. 2.9 Regional share of bioethanol production and consumption in 2011

bioethanol. Improvements in the technologies for bioethanol production as well as the use of the appropriate feedstock may render the fuel cost-effective in the near future.

In most parts of Europe and the USA, biofuel blending directives have been implemented. For instance in Sweden, gasoline is to be substituted by about 500 million liters of bioethanol every year. The largest biomethanol production plant in the world, which is located in Sweden (Värmlands Metanol AB) produces about 130 million liters of fuel grade biomethanol to replace gasoline. Throughout the world, there exists over 500 bioethanol production plants utilizing various feedstocks with most of them based in Brazil and the USA and these plants are able to contribute over 150 billion liters of bioethanol annually (REN21 2010). In the USA, large capacity bioethanol production companies like LS9 Inc. (which produces bioethanol from sugarcane), DuPont Danisco Cellulosic Ethanol LLC (a capacity of about 104 million liters of bioethanol from nonedible plants),⁹ Algenol (with a patented technology for bioethanol from photobioreactor grown algae), etc., are on commercial scale production. Chemrec AB, the first and largest biomethanol (164 million liters per year) and biodimethyl ether (DME) (117 million litres per year) production plant in the world is based in Sweden, which uses black liquor from pulp and paper mills as their major feedstocks (EIA 2011).

⁹ DuPont Danisco Cellulosic Ethanol LLC is set to begin operation in 2013. Presently, there is no company in the world producing commercial cellulosic bioethanol. However, companies like Novozymes, Diversa, Dyadic in the USA are currently developing efficient enzymes for the conversion of lignocellulosic materials into bio-ethanol. Again, in USA and some parts of Asia, over 20 companies have been testing their technologies on pilot scale since 2008 with the hope of commercializing by 2017 (Fehrenbacher 2012).

2.3.3 Other Liquid Biofuels (Bio-oils)

Bio-oil is a black liquid residue obtained from biomass hydrocracking and pyrolysis processes (Fig. 2.1). It has low energy density of about 17 MJ/kg than gasoline (about 39 MJ/kg) but high energy density compared to that for wood chips (about 4.5 MJ/kg) and straw (about 1.1 MJ/kg) (Lang et al. 2001; Akhtar and Amin 2011). With or without the addition of surfactants to bio-oils, they are very low in minerals and sulfur thus an attractive substitute for gasoline. Bio-oils are often used as boiler fuels and sometimes pretreated and combusted in diesel engines and turbines to generate electricity (Easterly 2002).

Apart from biodiesel and bioethanol, liquid biofuels such as pure plant oil (PPO) or SVO are common as fuels that are used in diesel engines in some parts of the world including the USA and the EU. PPO is produced by cold pressing of oil crops such as rapeseed, *Jatropha curcas* L., moringa, palm fruits which have successfully being used in diesel engines without modifications though they have high freezing points. Second-generation PPO (produced from SGF like *Jatropha curcas* L, karanj, etc.) are more sustainable compared to first generation ones that are produced from food crops. In some countries such as Finland and Singapore, SVO or animal fats are hydrogenated to form another important liquid biofuel, which is also used in diesel engines.¹⁰

Biokerosene is another liquid biofuel produced from oil seeds (by hydrogenation of the oils and liquefaction of gasified biomass), which is common in most rural parts of the world where electricity is not reachable. For instance, in developing countries such as Ghana, Tanzania, etc., *J. curcas* oil has been used as biokerosene in lamps as source of lighting in rural areas (Ofori-Boateng and Lee 2011). Rarely, biokerosene is used in aviation sectors to fuel jet engines due to its low freezing point and energy density (43.1 MJ/kg).

Pyrolysis oil also called bio-oil is the main product from the pyrolysis of biomass, which has been used as substitute for PD. Like tar, pyrolysis oil contains high levels of oxygen (40–50 %) thus slightly different in chemical characteristics compared to petroleum fuel hence not commonly used in fuel systems. Though the properties of pyrolysis oil depend on the kind of feedstock used, generally, they are acidic (pH of 2.7) and contain about 20–25 % water and 20–36 % sediments Sadaka and Boateng (2009) with lower heating value of 18.5 MJ/kg, flash point of 40–100 °C, pour point of –12 to –33 °C and cetane number of 10.

Pyrolysis oil usually cannot be easily blended with PD thus need special engine modification before use in its pure form in engines. For pyrolysis oil production processes to be more sustainable, the valuable components of the oil could be isolated and then the oil combusted to generate electricity or converted to syngas (Akhtar and Amin 2011).

¹⁰ This technology has not been tested on commercial basis yet (Bacovsky et al. 2010).

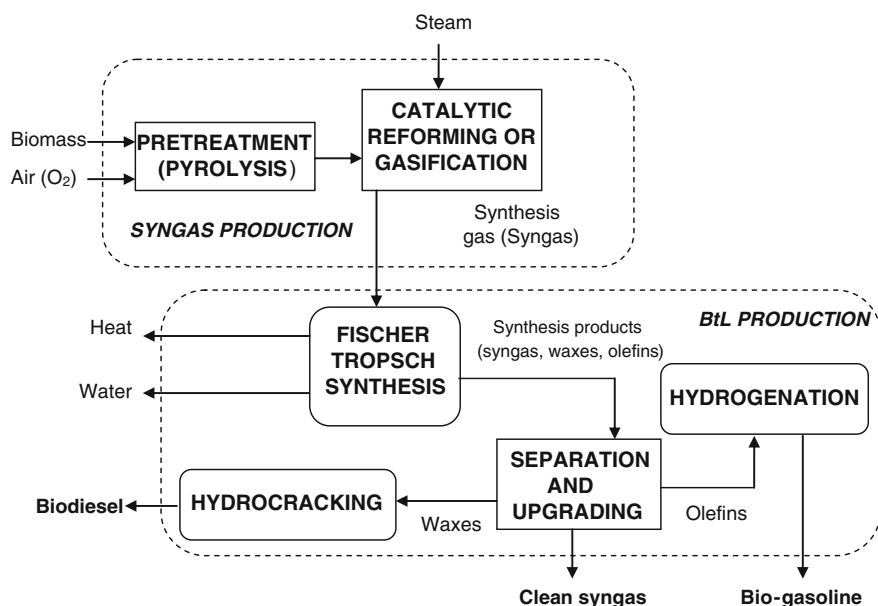


Fig. 2.10 Simplified flow diagram of BtL production process via the Fischer–Tropsch process

Biogasoline is also a type of liquid biofuel produced from algae biomass and cellulosic feedstocks like oil palm fronds, oil palm empty fruit bunches, switch grass, etc., through thermochemical processes (Fig. 2.1) such as pyrolysis.

Bio-Ethyl-tertiary-butyl-ether (ETBE) is also another type of liquid biofuel mostly synthesized from bioethanol and isobutylene in a catalytic reaction. It is mostly blended with gasoline in any proportion up to 15 % to improve its combustion properties before use in car engines. Bio-ETBE is found to be more compatible with engines than bioethanol, and it is mostly used in conventional vehicles and fuel distribution systems in the EU.

Gasification of biomass into syngas and then conversion into liquid biofuels (like biomethanol and biodiesel) by the Fischer–Tropsch process (also called the biomass-to-liquids technology, BtL) has been used to produce diverse liquid biofuels.¹¹ Unlike the fermentation of biomass into bioalcohols, BtL generates many potential compounds that are substitutes for liquid biofuels and other biochemicals. BtL products mainly produced from agricultural or forest wastes are more environmentally friendly with high GHG savings compared to those from grown energy crops like miscanthus (Jungbluth et al. 2007). Figure 2.10 shows a simplified flow diagram of BtL production process via the Fischer–Tropsch process.

¹¹ Biomass-to-liquid (BTL) biofuels also called Fischer–Tropsch fuels include synthetic diesel, bio-kerosene etc.

2.4 Gaseous Biofuels for Transport, Heat and Power Generation

Gaseous biofuels can be grouped into five, namely, biogas (commonly called biomethane), synthesis gas (biosyngas), synthetic natural gas, biopropane, and biohydrogen. They are mostly produced from feedstocks like sewage, animal waste, grass, leftover food, etc., through various processes such as anaerobic digestion (biochemical process), gasification (thermochemical process), etc. Gaseous biofuels are mostly characterized by their physical properties and chemical compositions based on the source of feedstock.

2.4.1 Biogas (Biomethane)

Biogas is a type of gaseous biofuel which comprises mainly methane (CH_4) and carbon dioxide (CO_2) as well as traces of hydrogen sulfide gas (H_2S), water, and siloxanes. It is commonly generated through the biodegradation of organic matter such as animal wastes, municipal wastes, industrial effluents, dead plant materials, energy crops, etc., in the absence of oxygen via a biochemical process. Depending on the type of feedstock and technology used for the biogas production, it can be alternatively called swamp gas, marsh gas, landfill gas, or digester gas. In most parts of the world, digester biogas is produced from animal wastes, organic industrial effluents, and food wastes. For instance, the dung from a cow could produce about 3 kWh electricity in a day, which is more than enough to power a 100 W light bulb which uses 2.4 kWh in a day. The calorific value of biogas is between 21 and 25 MJ/m³ implying that for 1 m³ of biogas, 1.7 kWh¹² electricity could be generated (Zhu et al. 2009).

One positive environmental impact of capturing biogas from cow manure other than allowing them decomposing without biogas capture is the reduction of global warming gases by 99 million tons or 4 % (Webber and Amanda 2008). For economic and environmental sustainability for the biogas production plant, biogas produced from byproducts of vegetable oil extraction and ethanol production as well as industrial effluents should be highly preferable.

Anaerobic digestion comprises four major processes, namely, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Bacterial hydrolysis decomposes the carbohydrates, fats, and proteins in the feedstock into sugar, fatty acids and amino acids, respectively. The products are then converted into carbon dioxide, hydrogen, ammonia, and other organic acids by acidogenic or fermentative bacteria.

The generated organic acids are further converted into acetic acid by acetogenic bacteria and finally, methane and carbon dioxide are formed as main products from

¹² An energy content of about 6 kWh is assumed (corresponding to about 0.6 l of diesel fuel).

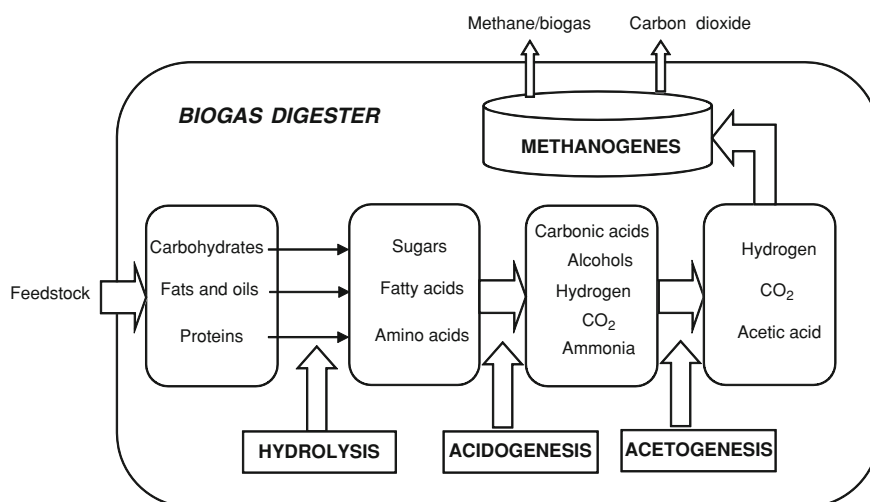


Fig. 2.11 Simplified process flow diagram of biogas production via anaerobic digestion

methanogenic bacteria (Song et al. 2004). These processes (especially the methanogenesis process) occur under controlled temperature, pH and pressure in order to attain the right kind of gases. The bacteria aiding the digestion could be mesophilic¹³ or thermophilic.¹⁴ The remaining residue or effluent from the digester can be used as organic fertilizer. Figure 2.11 shows the process flow diagram of biogas production from anaerobic digestion.

On the other hand, landfill gas is produced from wet organic wastes which decompose under anaerobic conditions with the help of bacteria in landfills either engineered or not. In an engineered landfill plant, the gas which is built up from the decomposed feedstock is captured, purified, and burnt in engines to generate bio-electricity. Landfills without gas recovery units may pose environmental problems as the methane generated from the site may contribute to global warming.

Presently, about 30 % of the biogas produced in the EU comes from sewage sludge and about 40 % originates from landfills. Before biogas could be transported or used in cylinders in cars, etc., they need to be purified. Water scrubbing technologies for biogas purification has been found to be one of the effective methods of rendering biogas compressible to be used in metal cylinders (Ofori-Boateng and Kwofie 2009). This technology is currently under application in Sweden where a 600 m³/h water scrubber is able to purify biogas produced by the Henriksdal sewage water plant in Stockholm.

¹³ Mesophilic microorganisms are the bacteria that aid anaerobic digestion and usually thrive well between temperatures of 20–45 °C and pH of 7.

¹⁴ Thermophilic bacteria operate efficiently at temperatures between 45 and 71 °C and pH between 2.3 and 5.

Generally, biogas is composed of about 50–75 % CH_4 , 25–50 % CO_2 , 0–10 % nitrogen gas, 0–1 % hydrogen gas, 0–3 % H_2S and negligible amount of oxygen, water vapor, ammonia, mercaptans, and other noxious gases (Zhu et al. 2009). However, the methane content could be increased to 80–90 % using advanced wastes treatment technologies with in situ gas purification unit (Richards et al. 1994). The calorific value of biogas is about 23 MJ/Nm^3 , which is about half that for natural gas. The energy in biogas is released upon combustion or oxidation with oxygen molecules in gas engines and can be used as fuel for the production of heat and electricity (Richards et al. 1994). In some parts of the world like United Kingdom, biogas is purified, compressed, and used in motor vehicles or stored in gas cylinders just like liquefied petroleum gas (LPG). In the USA, the use of biogas for electricity generation forms about 3 % of its total electricity expenditure. In most developing countries in Africa and Asia, biogas is mainly used as fuels for cooking and rural electrification. Though the efficiency of directly converting biogas to power and electricity through gas engines is low (about 20 %) compared to its use for heat supply and district heating (about 60 %), biogas is still used for power generation in most parts of the world. Apart from the commonly used application of anaerobic digesters for biogas production, landfills are also designed to produce biogas, which can be captured for use. Biogas can be used in a combined heat and power (CHP) gas engines for cooking and heating applications.

2.4.2 Biosynthesis Gas (Bio-syngas)

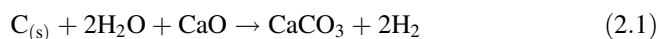
Bio-Synthesis gas, also known as biosyngas or bioproducer gas is an intermediate gas (produced together with hydrocarbon liquid and char) which comprises carbon monoxide and hydrogen (as main combustible components) that is produced by the thermochemical gasification of biomass (Maschio et al. 1994). Biosyngas has its energy density almost half that of natural gas hence used as transportation fuels. Biosyngas can also serve as a feedstock for the synthesis of synthetic natural gas, biomethanol, bioethanol, dimethyl ether, etc. The combined processes of gasification, combustion, and pyrolysis of biomass in a controlled manner could result in the formation of biosyngas, which can be combusted directly in internal combustion engines to generate electricity and heat.

Biosyngas can be produced from biochar (Chaudhari et al. 2003), bio-oil (Panigrahi et al. 2003) or steam reforming of biogas from gasification process (Chaudhari et al. 2001). Sewage sludge has also been found to be an effective feedstock for biosyngas production with the produced gas' calorific value to be $7000\text{--}9500 \text{ kJ/m}^3$ (Domínguez et al. 2008). The basic technology for producing biosyngas is the Fischer–Tropsch process (Fig. 2.9), which can occur in different routes. The thermochemical process can occur at high temperatures (about 1300°C) or low temperature (about 900°C) with a catalyst (Chaudhari et al. 2001).

2.4.3 Biohydrogen

Biohydrogen is hydrogen obtained biologically from biomass as an intermediate product from the production of biosyngas. The hydrogen as a component of biosyngas could be isolated through an appropriate purification process and directly used to power hydrogen fuel cells and electric vehicles for electricity production and transport purposes, respectively. Vehicles which are powered by hydrogen are about three times more efficient compared to gasoline powered engines (Jones et al. 2009). Apart from the use of hydrogen as transport fuels and electricity production, it is also used a reactant in hydrogenation and hydrocracking process to produce lower molecular weight compounds. It can also be used for as a good oxygen, sulfur, and nitrogen scavengers. Research and developments are ongoing on how to effectively develop an ecological method that could utilize bacteria to decompose the biomass to produce clean biohydrogen. Biohydrogen has a high energy content of about 33.3 kWh/kg (Demirbas 2004) and emits insignificant amount of environmentally toxic chemicals upon combustion.

Generally, the common technologies used for biohydrogen production from biomass worldwide include novel gasification processes (e.g., direct solar gasification, gasification coupled with water–gas shift process), pyrolysis, supercritical biomass conversion, microbial biomass conversion, biosyngas conversion, etc. After the generation of biosyngas from the Fischer–Tropsch process (Fig. 2.10), biological processes such as biophotolysis, biological water gas shift reaction and fermentation could be employed to separate and upgrade the biohydrogen from the biosyngas. Recent researches have proposed a more efficient method of producing biohydrogen directly from biomass by an integration of novel gasification reactions (HyPr-RING), which integrate the water–hydrocarbon reaction, water–gas shift reaction and absorption of gases in a single reactor under sub and supercritical water conditions (Sato et al. 2003; Lin et al. 2004, 2005). Figure 2.12 also summarizes the process flow of biohydrogen production. The reaction for the HyPr-RING process of biohydrogen production from biomass (carbonaceous material) is shown in Eq. (2.1):



2.4.4 Biosynthetic Natural Gas (Bio-SNG)

Bio-SNG is a kind of gaseous biofuel produced by the gasification (with methanation) of biomass mostly lignocellulosic materials like oil palm fronds. Bio-SNG has similar chemical compositions as biogas which is generated by the anaerobic digestion of organic wastes. Though bio-SNG production processes are found to be inefficient, bio-SNG can be synthesized from bio-syngas. Noncatalytic gasification at temperatures around 900 °C is reported to effectively produce high levels of methane (Heyne et al. 2010). Zwart et al. (2006) and Tunå (2008) have also

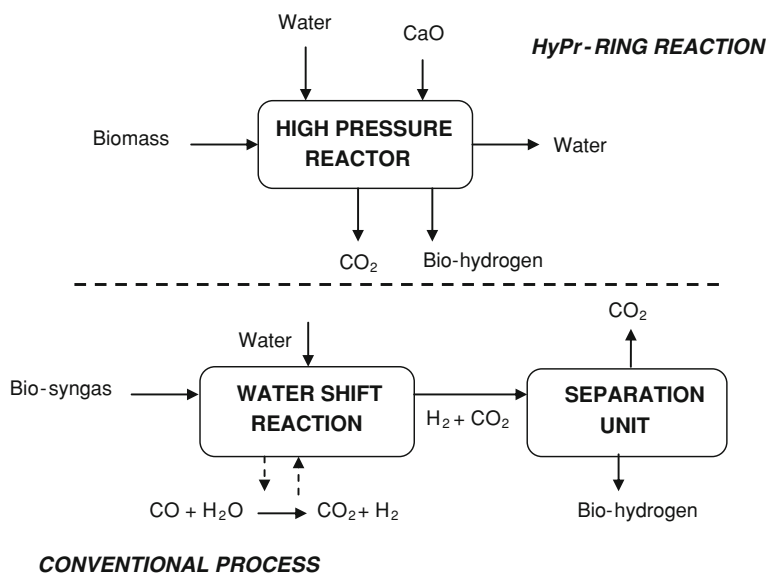


Fig. 2.12 Biohydrogen production from biomass by the HyPr-RING and biological water–gas shift reactions

demonstrated the possibility of generating bio-SNG from biomass in which direct and indirect gasification and methanation at atmospheric pressure were employed. A new technology called G4 bionatural gas process has been developed by the G4 Insights Inc. and Quest Air Technologies Inc. This technology is able to produce quality bio-SNG at high yields from biomass. Though bio-SNG has not gained much attention recently, Sweden (in Güssing) and Austria have initiated a pilot production since 2008 (IEA 2010). In Asian countries like Bangladesh, Armenia, and Pakistan, bio-SNG use in natural gas vehicles has reached a share of about 25 % of their total vehicle fleet (IEA 2010).

2.4.5 Biopropane

Biopropane is a kind of gaseous biofuel which can be synthesized directly from feedstocks like sugarcane bagasse, switchgrass, biocrude or vegetable oil, biosynthetic gas, glycerol, etc. Presently, in some parts of the USA and EU, biopropane production from lipid feedstocks is supported with federal grants, incentives, and tax programs. Biopropane production technologies include catalytic cracking of acylglycerides, single-reactor technologies, and bioreforming processes. The molecular structure of biopropane is similar to that obtained from petroleum-derived hydrocarbons thus can be blended with conventional propane and use for heating, power generation, and transport applications prior to upgrading.

2.4.6 Global Production and Consumption of Gaseous Biofuels

In Asia and Africa, biogas is produced on small scale for domestic purposes like cooking and residential lighting whilst in the EU, commercial production of biogas from their organic wastes and some types of cereals are available for heating and lighting. In 2009, out of about 230 PJ biogas¹⁵ produced in the EU, only about 10 % was used as vehicle fuel because the cost (about US\$ 5–15/GJ biogas) involved in upgrading the gas to avoid engine corrosion was very high (Tilche and Galatoo 2007).

In 2002, the world's total biogas production was estimated at about 92 PJ (with the highest growth rate of about 6 %) with Germany and England contributing the largest amounts (EIA EIA 2011). For instance in 2006, Germany alone had about 850 commercial biogas production plants accounting for about 80 % of the total number of biogas plants in the world by then. The amount of bioelectricity generated from the total biogas produced in the EU in 2006 was about 17,272 GWh of which about 7,338 GWh was contributed by Germany alone (IEA 2010). Biogas used in electrification in Germany contributes about 10 % to the total energy generated from renewable sources. In addition, the EU currently has over 650,000 biogas-powered vehicles running smoothly on their roads as a way of contributing to the move for biofuels sustainability in the near future. Countries like Spain, Sweden, Italy, New Zealand, and Australia also contribute significant share to the world's biogas market. By the end of the year 2020, the world is projected to hit a total of about 779 PJ of biogas production capacity (EIA 2011).

However, the biogas market is still at its infant stage and embodied with a lot of challenges such as high feedstock prices, turmoil in the global credit markets, etc. Supportive government policies in terms of subsidies, incentives, and investments have rather helped boosted the biogas market from collapsing gradually. Presently, the cost of biogas is about € 0.16/kWh. According to the report by Global Industry Analysts Inc., the world's biogas market is forecast to reach about US\$ 8.98 billion by 2017. This target would be realized when the urge for reduced dependency on fossil fuels as well as the adoption of efficient methods in production backed by government incentive programs are pursued.

In African countries like Ghana, Tanzania, South Africa, Nigeria, etc., there are millions of biogas plants existing but they operate on only small scale and the biogas from these plants are mostly used for household purposes like cooking. The bigger capacity plants are mainly constructed for hospitals, slaughter houses and big institutions for the purposes of good sanitation. In India, about 1.8 million biogas digesters have been installed since 1990 with their main feedstock being cattle dung. However, by 2005, only about 1.7 million biogas plants were operational (ESMAP 2005). Rural electrification in India is about to be realized with

¹⁵ This biogas is produced from over 4500 commercial biogas digesters and landfill sites excluding the millions of small scale ones.

biogas plants under construction with capacity of about 60 kW electricity output (ESMAP 2005). In North America and the USA, there are a few number of biogas plants for medium- and small-scale biogas production. The contribution of commercial production of biogas for electrification to the public grid in these regions has not been realized much due to the low feed-in tariffs (of about EUR 0.05/kWh), which do not make the production profitable (Copel 2009). Though other gaseous biofuels are being used in some parts of the world, their production and consumption capacities are insignificant. Biopropane, for instance, is set to be produced commercially in some parts of Europe and the USA with capacities ranging from 150,000 to 180,000 tons/year (EIA 2011). It would soon be available on the biofuel market as a substitute for LPG and used for transportation purposes.

2.5 Solid Biofuels for Heat and Power Generation

Biofuels in the form of solids have been in use since man discovered fire for heating. Wood, mostly called firewood, was the first solid biofuel used by the ancient people for cooking and heating until some few decades ago when man discovered alternative ways of utilizing those solid biofuels for cleaner energy production. Currently, most sustainable feedstocks for solid biofuel production are lignocellulosic materials such as forest residues, sawmill wastes, agricultural residues, etc., as they are abundant with limited utilization for value-added bio-products. In the USA alone, about 95 million dry tons of primary crop residues like corn stovers, wheat straws, rice husks, oat brans, etc., are readily available as wastes for use as solid biofuels. All these wastes could be termed as solid fuels as they can directly be combusted to produce energy for many purposes in all sectors of the economy. This production capacity is projected to double by 2030, which shows a good potential for use as solid biofuels with constant generation. Surprisingly, all other types of biofuels are produced from these solid biofuels. Table 2.4 summarizes the benefits and disadvantages of the three types of biofuels discussed in this chapter. In this section, the main solid biofuels to be discussed are grouped into four namely:

- Woody biomass.
- Herbaceous biomass.
- Fruits and vegetables biomass.
- Blends of two or more of the solid fuels.

Woody biomass is sourced from trees, bushes, and shrubs whilst herbaceous biomass is obtained from plants that are nonwoody and decompose at the end of their growing seasons. Examples include grains, cereals, etc. Fruits and vegetable biomass are obviously obtained from the flesh or seeds of fruits and vegetables such as *Jatropha curcas* L., oil palm, etc.

In most parts of the world, the most marketed solid biofuels include briquettes, pellets, hog fuel, wood chips, log wood or firewood, biochar, wood shavings,

Table 2.4 Advantages and disadvantages of the types of biofuels

Biofuel type	Advantages	Disadvantages
1. Liquid biofuels	1. Easy to handle 2. Can be transported easily through pipelines 3. Do not leave any residue after combustion 4. Have higher calorific values compared to solid biofuels 5. Produce little or no smoke upon combustion 6. Have relatively low ignition temperature hence burn easily than solid fuels	1. Highly flammable 2. Production technologies and the products are expensive
2. Gaseous biofuels	1. Convenience to use as they don't require any pouring nor priming 2. Can be transported through pipelines 3. Do not leave smoke residues after combustion	1. It produces energy in a less effectively manner at subfreezing temperatures than liquid fuels 2. Highly flammable 3. Difficult to handle 4. Expensive compared to liquid and solid biofuels
3. Solid biofuels	1. Less costly compared to liquid and gaseous biofuels	1. Technology is complex and costly 2. Are environmentally polluting compared to liquid and gaseous biofuels

sawdust, trees bark, straw bales, reed canary grass bales, miscanthus bales, olive residues, energy grains, dried manure, fruit and vegetable seeds, etc. The energy from these fuels is released upon combustion and the combustion conditions may affect the efficiency of the generated energy. Biochar is another important solid biofuel which is produced during pyrolysis.

Briquettes are solid fuels formed from the compression of dried wood chips into small logs or cylinders usually of about 25–70 mm in diameter and 20–25 cm in length (Hosier and Svenningson 1987). Briquetting is usually carried out in order to reduce the bulky nature of the wood chips for easy storage and transportation. Briquettes are normally co-fired together with coal in large power plants for the generation of heat and bioelectricity. Although there are many briquetting plants installed in most parts of the world, they have not been successful due to difficulty in the supply of raw materials and low technological efficiency coupled with high cost of production (Hosier and Svenningson 1987). Briquettes, just like all other solid biofuels normally burn with smoke resulting in environmental degradation thus technological improvement could improve the sustainability of solid biofuels production.

Pellets are solid biofuels with similar properties to briquettes except that pellets are much smaller in dimensions. Pellets are produced firstly by drying the wood

chips and grinding then finally extruding under intensive pressure to form the basic shapes. Wood pellet has calorific value of about 18 GJ/ton, which is about half that for fuel oil. Norway is currently among the largest pellets producing countries in the world with a production capacity of about 15,000 tons/year. As at 2010, Russia began producing pellets (with production capacity of about 900,000 tons annually) from the solid residues of their pulp and paper companies, which are used in the generation of heat and electricity. Pellets are also used directly in stoves and furnaces for heat generation in most parts of the world.

In most rural areas of the world, solid biofuels like firewood can directly be burnt in stoves or furnaces to generate heat for cooking and other purposes. Sawdust, woodchips, grass, agricultural residues can also be compacted and directly fired in furnaces and stoves for heating. Tree barks and large agricultural residues are also burnt to produce charcoal, which can be used in stoves to generate energy and use for other various purposes such as the production of reducing agents used in the metallurgical industry. However, more than half of the energy content in these woody materials is lost when they are converted into charcoal. In industrial boilers, solid biofuels such as palm kernel shells, charcoal, etc. can be used to generate clean power. Presently, charcoal production is based on traditional carbonization technology whilst the fast pyrolysis of biomass into charcoal under high pressure is not on commercial scale.

One major problem associated with the combustion of solid biofuels is the considerable amounts of pollutants that they emit. However, the degree of pollution may depend on the type of solid biofuels used. For instance, pellets made from agricultural residues are usually more polluting than wood pellets. Even though solid biofuels emit large amount of dangerous gases, they are better than fossil fuels (see [Chaps. 5–7](#)).

2.6 Market Barriers of Biofuels

Compared to fossil fuel, international biofuel trade is nascent. For instance, the international trade of biodiesel and bioethanol among the EU, the USA, and other countries is very small. Basically, the EU consumes its own biodiesel despite the fact that they are the leading producers who must expand their market to the smaller ones. This has been one of the major barriers to the biofuel market growth. Biofuels are currently traded between close neighboring countries and regions of the world and as the biofuel market expands, there would be the need to strengthen possible international trade relationships among countries. Challenges that are faced with the biofuel market originate from the trade with their feedstocks though there exist high international trade relationships between most countries of the world concerning the trade of vegetable oils. For instance, Malaysia and Indonesia have been exporting their palm oil to the EU and the USA to be processed into biodiesel because the EU and the USA have the lead in biofuels technological advancement. The international trade of most oils for biofuels is restricted by

tariffs and other migration measures. Imports of biodiesel into the EU are subject to an ‘ad valorem duty’ of about 6.5 % (Doornbosch and Steenblik 2007). Nowadays, large quantities of bioethanol are traded for alcohol beverages, as solvents for industrial applications due to the high cost of bioethanol fuel (without subsidies) on the international market compared to fossil fuels. Brazil still stands as the world’s leading exporter of bioethanol fuel accounting for more than half of the world’s total trade for liquid biofuels. In Africa, though sugarcane is grown in large quantities, bioethanol production is very low due to lack of technology, policies and investments. However, some of the African countries export their sugarcane to other countries to be processed into bioethanol. The major solution to these challenges would be the enactment of standardizations for biofuel production as well as incentives and subsidies for producers. The biofuel market may realize tremendous growth when attractive policy measures are enacted and at the time when fossil fuels finally are exhausted and their prices exceed those of biofuels.

One major barrier to the production and use of biofuels globally is their high cost. For instance, presently, bioethanol production cost is between US\$ 0.20 and US\$ 0.97/l depending on the feedstock type (Cornland et al. 2001). Bioethanol production from sugarcane (i.e., the sugar) is lower compared to the others with sugar beet bioethanol having the highest production cost. This is due to the high cost of raw materials mostly FGF, which compete with food for land and other resources. Figures 2.13 and 2.14 show the market trends in bioethanol and biodiesel production, respectively.

Technological barriers continue to exist as another challenge to the growth of the biofuel market. Biofuel production processes are energy intensive and consume a lot of fossil fuel during their production hence presenting them costly. Again, process optimization and efficiencies are sometimes complex to achieve especially in the case of bioethanol production from lignocellulose. Also, lack of capital

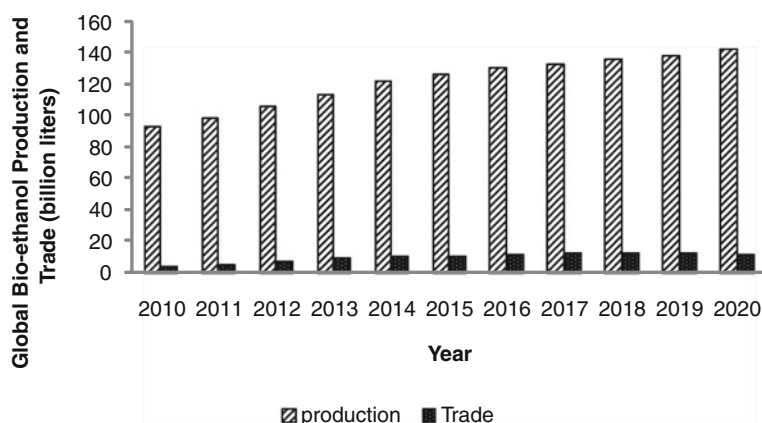


Fig. 2.13 Trend in the global production of bioethanol (OECD-FAO 2011)

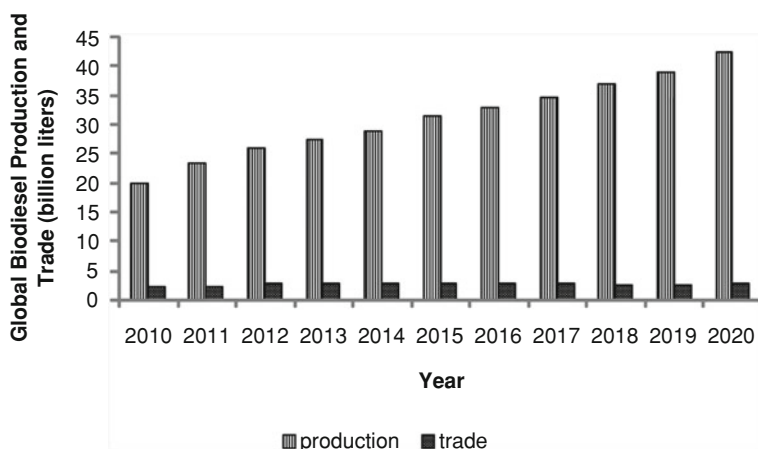


Fig. 2.14 Trend in global biodiesel production and trade (OECD-FAO 2011)

coupled with high transaction costs involved with the production of biofuels have been the contributing factors to the technical barriers to its market growth. Apart from some few biofuels like biodiesel that could be produced on small scale without complex infrastructure, most of the biofuels production could not do without such equipment and infrastructure. For instance, the production of gaseous biofuels especially requires much profound and complex infrastructure to operate successfully and achieve better efficiencies.

Another barrier is in relation with trade. Some types of biofuels do not have specifically laid down sustainability standards and criteria and yet, they are being produced in commercial quantities. This presents the biofuel much more expensive and unattractive compared to fossil fuel presently. For instance, due to lack of laws and regulations on denaturing obligations on bioethanol trade, there exist many trade barriers for its market internationally. The failure of the end users of biofuels to value the products and know the advantages they have over the conventional fuels has been another limitation to the growth of the biofuel market. For instance, the use of some biofuels need engine modification, which create inconveniences to customers hence limiting the market for biofuels. The end users of biofuels mostly lack more knowledge about biofuels and their use.

Another limitation to the growth of biofuel market is attributed to commercialization. FGB are the most abundant type of biofuels under commercialization nowadays. However, with the hope of achieving sustainability, SGB, TGB, and fourth-generation biofuels are encouraged. Yet, commercialization of bioethanol from lignocellulosic materials (which are mainly wastes), for instance, has not been realized much until today though some commercial and pilot productions are ongoing.

2.7 Conclusion

There are many types of biofuels produced and consumed in the world today and these may exist in liquid, solid, and gaseous forms that could be used for various applications. The development of biofuels production technologies is vital for sustainable development because the yield, cost, and environmental impacts may not be encouraging if inappropriate technologies are employed. The production and consumption of biofuels worldwide are recording tremendous growth especially with first-generation biofuels like biodiesel from rapeseed oil. With process improvement in biofuels production technologies, sustainable biofuels development may be realized in the near future.

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Part II
Biofuels Production from Oil Palm
Biomass and Sustainable Development

Chapter 3

Oil Palm Biomass as Feedstock for Biofuel Production

Abstract Palm oil is currently the cheapest vegetable oil on the world's international market. The oil palm in general is found to be the most productive crop in terms of oil yield per cultivated area. The palm oil industry in the world generates over 190 million tons of wastes in the form of solid and liquid residues. Out of this only about 10 % are utilized commercially for value-added bioproducts like bio-fertilizers. Oil palm biomass is found to possess unique characteristics which make them suitable for the production of biofuels. This chapter discusses into detail the various forms of oil palm biomass, their characteristics, and potential applications in the biofuels industry.

Keywords Oil palm biomass • Crude palm oil • Palm biofuels • Oil palm • Oil palm wastes • Palm oil mill effluent • Palm kernel oil • Palm fatty acid distillate • Oil palm frond • Palm pressed fiber • Palm kernel shells • Palm olein • Palm stearin • Palm empty fruit bunch • Oil palm trunk • Oil palm leaves • Oil palm root

3.1 Introduction

Biomass is defined as the organic matter which is constantly available on renewable basis and could be in the form of solid or liquid with examples including forest and mill residues, agricultural wastes, etc. Thus, oil palm biomass comprises all organic matter, be it edible or non-edible, liquid, or solid that is generated by the oil palm industry during plantation, palm oil milling, refining, palm kernel oil milling, etc. The oil palm industry is found to be one of the largest producers of biomass mostly in the form of wastes. In 2011, Malaysia and Indonesia (being the largest producers of palm oil in the world) together generated nearly 182 million dry tons of oil palm solid biomass which is projected to increase to about 230 million tons by 2020 (MPOB [2012](#)). The oil palm again

yields about a threefold, sevenfold, and tenfold more oil than coconut, rapeseed, and soybean, respectively (Schmidt 2007). The oil palm is capable of producing as much as 4000–5000 kg of crude palm oil (CPO) and 400–500 kg of palm kernel oil (PKO) per hectare of cultivated land (MPOB 2012). As the world's population keep rising and fossil fuels being at the verge of depletion, there are high demands for oils and fats both for food and fuels. Palm oil may help offset most of the challenges to be faced in this regard as there may be the need for minimal land area for producing high volumes of oils and fats of which the oil palm is the best candidate. Oil palm biomass is therefore seen as a major wealth contributing source for biomass utilization industries whose objectives may be geared toward energy production.

The constant availability of feedstocks for biofuel production has been a major challenge to the biofuel industry. Currently, over 95 % of the world's total biofuels consumed are commercially produced from edible crops like sunflower oil, rapeseed oil, corn, etc., which have constantly raised much debatable issues on food versus fuel delineation. The oil palm tree, however, is the most productive plant in the world which produces huge amount of biomass in the form of food and wastes which could be transformed into biofuels other than them laying bare in the environment creating havoc. The oil palm is cultivated in more than 45 countries in the world on a total land area of about 12.9 million hectares (GOFBM 2009).

Oils from the palm fruit (i.e., mesocarp and kernel oils) form the largest share of the world's current edible oil's consumption and their huge demand especially the mesocarp oil, has resulted in the expansion of the oil palm industries worldwide and this has further facilitated the generation of large amount of oil palm wastes (OPW). OPW are mainly generated from the plantation after harvest and milling processes. About 10 % of the whole palm tree produces oil in the form of mesocarp oil (palm oil) and palm kernel oil. The remaining 90 % comprises the fronds, leaves, trunk, roots, etc., which are mostly considered wastes. For a hectare of cultivated land, the oil palm industry generates close to 70 tonnes of OPW every year (Salathong 2007) making up to a total of about 184 million tons OPW in the world annually with about 5 % annual increment in these values (GOFBM 2007).

There are many kinds of bioproducts including biofuels which could be produced from both the palm oil and wastes in order to present it more sustainable. The oil palm biomass possesses good characteristics which make them highly appropriate as feedstocks for biofuel production. All three types of biofuels namely solid, liquid, and gaseous biofuels can be generated from oil palm biomass. This chapter outlines the types of oil palm biomass, their characteristics and generation profile in the world at present. Figure 3.1a–i shows the pictorial diagrams of the types of oil palm biomass mainly considered as biofuel feedstocks.

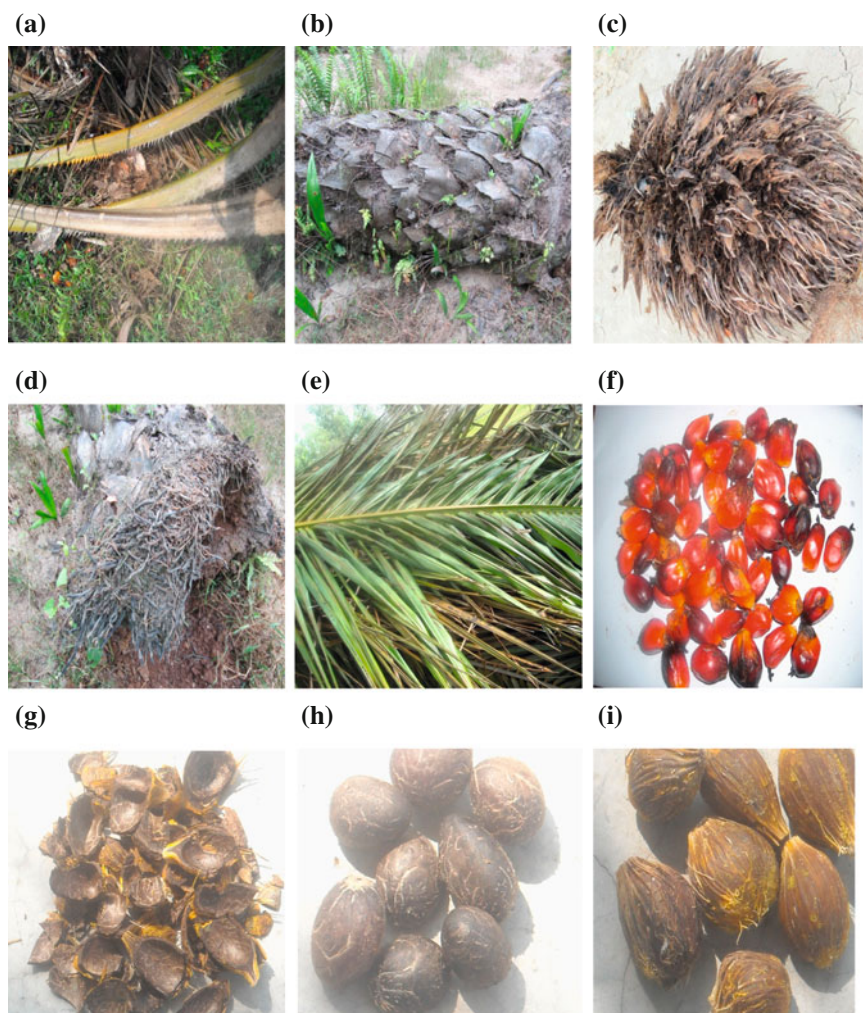


Fig. 3.1 Major types of oil palm biomass used as feedstocks for biofuel production. **a** Oil palm fronds, **b** Oil palm trunks, **c** Oil palm empty fruit bunch, **d** Oil palm roots, **e** Oil palm leaves, **f** Oil palm fresh fruits, **g** Palm kernel shells, **h** Palm kernels, **i** Palm kernel seeds

3.2 The Oil Palm: History, Botany and Varieties

3.2.1 Origin and Distribution

The oil palm is a widely cultivated oil bearing tropical palm tree which originated from West Africa (specifically the rain forest of Guinea) and initially illustrated by Nicholaas Jacquin in 1763. In the late 1400s, the European visitors who were

dwelling around the coast of Guinea discovered the oil palm trees (Poku 2002). By 1508, palm groves had been recognized in nearby countries such as Liberia and Nigeria (Poku 2002). Later, during the era of slave trade, the oil palm spread throughout most parts of Africa from areas located around 16° North of Senegal to 15° South of Angola through the Eastern parts of Zanzibar and Madagascar (Henderson and Osborne 2000). Though the climate in most parts of East and South Africa are not favorable for palm cultivation, few do thrive at altitudes below 1000 m near lakes or water bodies with considerable amounts of rainfall. Its presence on the eastern coast of Madagascar was due to a local microclimate though in this area the crop could be affected by tornados. The real palm belts in Africa initially was running through Ghana, Cameroon, Cote d'Ivoire, Liberia, Nigeria, Sierra Leone, Togo, Angola, and the Republic of Congo. It later spread to other parts of Africa and regions of the world including South America and Asia between the fourteenth and seventeenth centuries (Henderson and Osborne 2000; Poku 2002). The first African oil palm which was brought to Asia by the Dutch were initially grown in the botanical gardens of Bogor, Java as ornamental plants. Nonetheless, an intensive oil palm research and developments in Singapore, Malaysia, and Indonesia (specifically Deli Research Centre in Sumatra) brought forth important benefits of the oil palm since the early 1900s. The oil palm gained international acceptance when the demand for palm oil as lubricants for steam engines, machinery, and as major raw material for soap manufacturing rose in the late nineteenth century. The oil yields and quality of the oil palm cultivated in Asia are still superior to that produced in other parts of the world. South America also contributes to significant share in the global production of oil palm presently. The oil palm is found to thrive very well in areas of high rainfall within the isohyets of 1200 mm rain per year with a topography of about 400 m altitude and tropical climates within 70° North and South from the equator (Schmidt 2007). Till today, the oil palm industries in Africa, Asia and America have expanded with Indonesia and Malaysia being the leading producers of palm oil in the world. In 2010, Malaysia cultivated about 4.6 million hectares of oil palm which was able to produce about 17.6 million tons of palm oil and about 0.7 million tons of palm kernel oil (MPOB 2012).

3.2.2 Taxonomy and Propagation

The classification of the cultivars of the oil palm is mainly done based on the fruit structure and the yield on commercial value. The oil palm is a vascular perennial monocotyledonous insect pollinated (mostly by the weevil *Elaeidobius kamerunicus*) seed plant (or tree) (MPOPC 1996). Male flowers of the oil palm that are mostly pollinated are anise-scented. Assisted pollination is done in modern plantation in order to increase the oil yield. The oil palm seeds that are distributed naturally do not germinate readily as they may need favorable seasonal conditions to thrive well. In West Africa, they remain often dormant during the dry season

and start germinating from 6 to 10 weeks at temperatures in the range of 30–40 °C for 80 days after the start of the first rain (Schmidt 2007).

After about 4–5 months when the seedlings reach the 4–5 leaf-stage, they are transferred to nurseries or large polythene bags where they grow for 6–12 months before transplanting to the main plantation field. The commonly used oil palm planting density and spacing are 128–148 palm seedlings/ha and 9 m × 9 m triangular space, respectively, depending on the type of soil and climatic conditions (Schmidt 2007; Xavier et al. 2008). The normal frequency of harvesting is between 10 and 15 days (Xavier et al. 2008). The oil palm tree produces averagely 12 fresh fruit bunches (FFB) annually with a bunch weighing about 15–25 kg and containing 1000–1300 fruitlets depending on the plantation management and establishment methods. On a per hectare basis, an oil palm plantation can yield averagely 35 tons of FFB (from about 148 palm trees) and 8.6 tons of palm oil (Schmidt 2007).

The oil palm belongs to the Kingdom *Plantae*, Subkingdom *Tracheobionta*, Superdivision *Spermatophyta*, Division *Magnoliophyta*, Class *Liliopsida*, Subclass *Arecidae*, Order *Arecales*, Family *Arecaceae* (or *Palmae*), and Genus *Elaeis*. The main species of the oil palm are the *guineensis* and *oleifera* (or *melanococca*). However, there are many other species which have evolved from these two major species including *dura*, *deli*, *kamerunicus*, *macrocaria*, *pisifera*, and *tenera*.

Elaeis guineensis Jacq. has been the most common oil palm variety with an average generic life span of 150 years and significantly high oil-to-bunch content (45–55 % oil) compared to the other varieties (Schmidt 2007). In Central and Western parts of Africa, the *dura* and *guineensis* are the major species found. The *dura* has thick endocarp of thickness 2–8 mm which forms about 25–55 % of the weight of its fruit. The *dura* is less productive with medium mesocarp thickness of about 35–55 % of its fruit's total weight (Alvarado et al. 2007). The *deli* has medium mesocarp thickness of about 35–65 % by weight of the whole fruit whilst the *pisifera* is shell-less with very thick mesocarp and has small pea-like kernels within the fruits (Alvarado et al. 2007). The *pisifera* has little commercial value due to its prematurity as a result of flowers rapturing off earlier than maturity. However, for commercial use, it is worth cross-breeding for high oil yield hybrid varieties. The *tenera*, a hybrid of the *dura* and *pisifera*, has thin endocarp of about 0.5–3 mm thick which is about 1–32 % of the weight of its fruit with a medium to high mesocarp thickness of about 60–95 % of weight of fruit and their kernels weigh about 3–15 % of fruit (Alvarado et al. 2007). The *tenera* is the species with very high commercial value compared to the others. Compared to the *dura*, *tenera* has larger number of bunches but lower mean bunch weight and lower fruit to bunch ratio (Alvarado et al. 2007). However, the *tenera* and *pisifera* yield a lot of oil per hectare compared to the other varieties. In Malaysia, Indonesia, and some parts of Asia, the *tenera* and *guineensis* are the common species found. The *oleifera* and *kamerunicus* are mostly found in South America with rare availability of the *guineensis* Jacq. The *oleifera* has been reported to have higher levels of unsaturated fatty acids and are mostly used for the production of interspecific hybrids with the *guineensis*. The *macrocaria* is an extreme or wild form of the

dura and has an endocarp of about 6–8 mm thick (Corley and Tinker 2003; Alvarado et al. 2007). It is commonly cultivated in Sierra Leone and Nigeria without any commercial value.

The oil palm industry now focuses on genetic means of improving the oil yield, disease tolerance, and the height of the tree (like breeding dwarf palms in order to prolong the economic cropping cycle). Corley and Lee (1992) and Pushparajah (2002) have reported the possibility of commercializing genetically bred oil palms for the next 15–40 years. However, currently, transgenically high oleic acid palms have been field tested and proven to be better (Ravigadevi et al. 2002).

3.2.3 Botanical Description

The oil palm is allogamous (i.e., cross-pollinated) and propagated by the seeds with an average generic life span of 150 years and an economic life of 20–25 years (Schmidt 2007). The genome size of the oil palm is 1.95×10^9 base pair (Rival et al. 1997) with a haploid chromosome number of 16 as reported in the cytogenetic analysis by Maria et al. (1995). The oil palm has a crown of about 35–60 pinnate fronds that are arranged on a vascular stem. It has a single bud in the base of the crown where fronds and inflorescences originate. Flowering starts after the young palm is well established. Each flower primordium which is formed in the axil of the frond is a potential producer of male and female inflorescences. The oil palm has both male and female flowers (i.e., monoecious) that are clustered in short inflorescences and produces about 1000–3000 fruitlets (that are fleshy, about 2–3 cm long and oblong-ovoid in shape) that are also clustered in bunches with weights ranging between 10 and 30 kg (Schmidt 2007). An inflorescence primordium is produced in the axil of each leaflet at the time of the leaflet's initiation. The number of inflorescences per oil palm tree depends on the number of leaves produced and the number of inflorescences which reach maturity without abortion. Male and female inflorescences form separately on the same oil palm tree. A male inflorescence produces about 10–40 g of pollen. A female inflorescence consists of a central stalk or peduncle where leaf spikelets are attached and where the coloured female flowers are found. The development of the inflorescences to the fruit regime takes a total of about 40–42 months with the establishment to initial sexual differentiation taking 10 months: from sex development to flowering taking about 24–26 months and from flowering to fruiting lasting for 5–6 months (Schmidt 2007). The oil palm fruit bunch is tightly wedged in the leaf axil of the palm. A bunch of a matured oil palm fruit contains about 1000–4000 fruits depending on the age and growth pattern of the tree. A matured oil palm tree is an erect single-stemmed plant of about 25–30 meters in height and with pinnate leaves of lengths 3–5 m each (Schmidt 2007). The oil palm leaves are produced in spiral succession from the meristem and bear about 50–60 lanceolate and pointed segments with the petioles marginally spiny and toothed. A leaflet is produced every month until the maturity of the tree has reached 6-month old. The leaf area of an adult oil palm tree

is about 400 m². The crown consists of about 40–50 leaves that are opened in various stages of development. After 24–30 months of planting an oil palm tree, it begins to bear the fruits (which are initially dark-green or almost black in color which later becomes yellowish-red in color with the size of large plums in large bunches when fully ripened). At maturity, an oil palm fruit bunch weighs about 15–50 kg. The fruitlet of the oil palm has four main parts namely the exocarp, mesocarp (or the pulp), endocarp (kernel nut), and the kernel seed. The exocarp is the outer shell of the fruitlet which is yellowish red in colour. The mesocarp contains the fibres which are filled with palm oil. The endocarp is mainly the outer layer of the kernel seed and when cracked, would expose the kernel which contains the germ. Palm kernel oil is obtained from the kernel seeds when cracked and pressed. The oil contents in the pulp and kernels are about 50–60 % and 45–55 % respectively (Schmidt 2007). Figure 3.2 shows the picture of the various parts of the palm fruitlet.

The roots of the oil palm tree emerge from the base of the hypocotyl and later from the basal bole of its stem or trunk. When the water table is high, primary roots develop down the base of the trunk and remain short. On the other hand, when the water table is low, the oil palm tree produces secondary, tertiary and quaternary roots which form a dense platform in the surrounding areas of the tree. Most oil palm roots are found within the top 15 cm of the soil. The early growth from the seedlings results in the formation of a wide stem base. After about 3 years, the apex of the oil palm tree attains its full diameter which forms an inverted cone with an intermodal elongation emerging as the trunk. The rate of extension of the trunk which could vary between 25 and 50 cm per year (Dransfield et al. 2008) depends largely on the environmental and hereditary factors.

3.3 Oil Palm Cultivation and Productivity

The cultivation of oil palm requires several field work practices such as raising of seedlings, sowing of crop cover, herbicides, pesticides, and fertilizer applications, harvesting, transportation of FFB to milling sites and land preparation again for replanting (Schmidt 2007). Prior to land preparation for nursery and transplanting of oil palm seedlings, a feasibility study (normally called the planning stage) of the proposed area which involves the environmental impact assessment (EIA) and other measures to ensure the sustainability the oil palm plantation are carried out. In Malaysia for instance, the suitability of the proposed area must be endorsed by the respective bodies for land acquisition and agriculture before nursery and subsequent plantation proceeds.

Basically, there are two types of oil palm nursery practices namely single and double stages. In single stage nursery, the seedlings are raised in big polythene bags till they are ready for transplanting on the main plantation field. For the double stage nursery which is commonly practiced, the seeds are sown in small polythene bags (15 cm × 23 cm) under protective sunlight or shade until

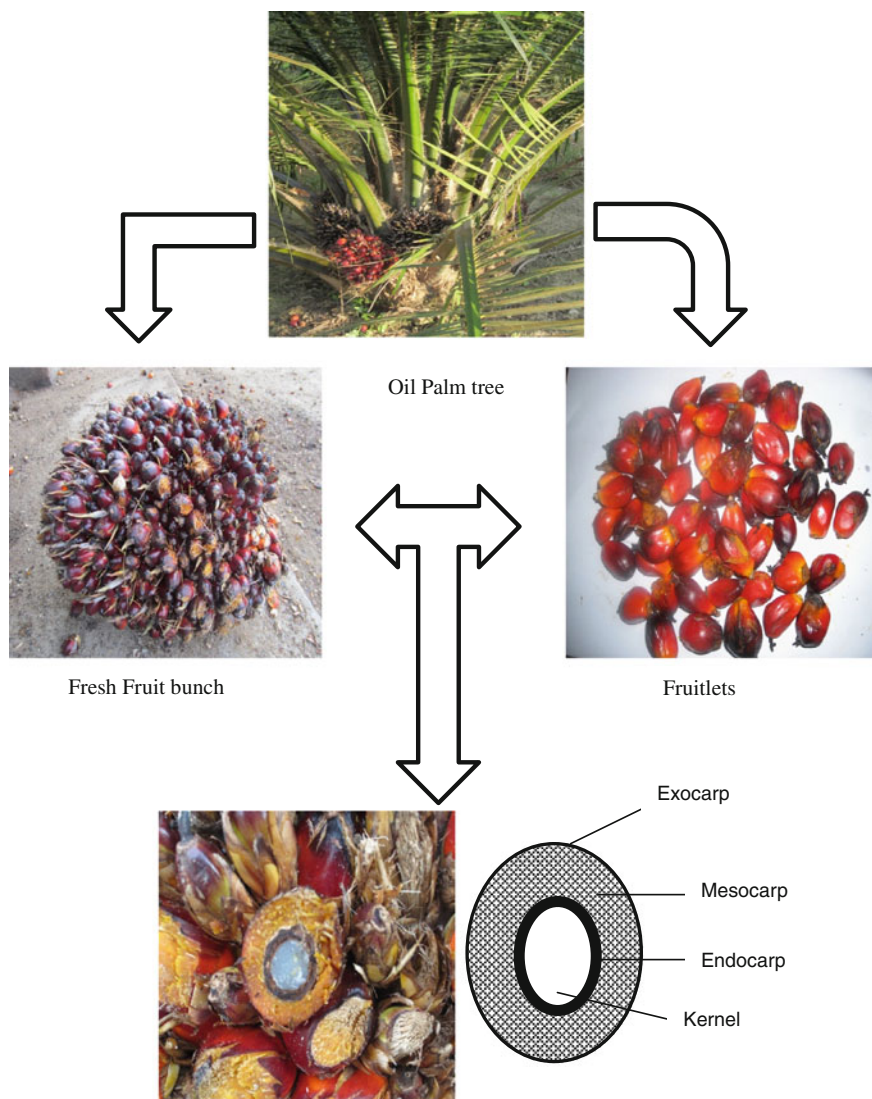


Fig. 3.2 Diagram showing the parts of the oil palm fruitlet

3–4 months old after which they are again transferred into bigger polythene bags (30–38 cm × 38–45 cm) and again raised under direct sunlight until ready for transplanting onto main plantation field (Corley and Tinker 2003; Singh et al. 1999). After about 12–14 months, they are transplanted to the appropriate plantation area which has already being prepared with proper creation of roads and paths as well as water drainage systems.

Oil palm seedlings are normally raised in polythene bags using the palm kernel seed which could be stored for more than a year. Mostly, low amounts of fertilizers with adequate irrigation (about 0.5 l and 1.5–2.5 l of water per polythene bag per day for small and big polythene bags, respectively) are applied at this stage to ensure proper growth of the seedlings (Corley and Tinker 2003). The common type of pesticide used in the nursery is dithiocarbamate which in fact has negative impacts on the environment. One major call for alarm during oil palm land clearing (which may contribute to unsustainable cultivation) is bush burning which is environmentally unsafe and could contribute to tremendous loss of biodiversity. Oil palm is often interspersed with leguminous crops for addition of soil nutrients and control soil erosion. These may not be enough as the use of fertilizers are required at this stage of planting. When the trees are quite matured to some extent (not to the time of harvesting), field maintenance practices such as pruning, pest and disease control as well as mulching (normally with pruned fronds and leaves) are carried out. The commonly used oil palm planting density and spacing are 128–148 palm seedlings/ha and 9 m × 9 m triangular space, respectively, depending on the type of soil and climatic conditions (Schmidt 2007; Xavier et al. 2008). The oil palm requires evenly distributed rainfall between 1800 and 5000 mm/year. The normal frequency of harvesting is between 10 and 15 days (Xavier et al. 2008).

After 24–60 months¹ of transplanting depending on the nutritious value of the soil and other factors, harvesting of FFB may be due (Corley and Tinker 2003). Harvesting and collection of harvested fruits are done manually with levers like wheelbarrow, sickle, etc. In order to ensure minimal amount of free fatty acid (FFA) content of the oil, handling of FFB after harvesting must be done in a way to reduce bruises on the fruits. Also, since the quality of the oil produced depends on the time interval between harvesting and sterilization (the first stage of milling), FFB must be transported as soon as possible after harvesting and the distance from plantation to milling site must be short.

The oil palm is presently cultivated in more than 45 countries in the world on a total land area of about 12.9 million hectares (GOFBM 2009). Oil palms are highly efficient producers of oil requiring less land than any other oil-producing crop.² Of all the commercial vegetable oil crops in the world today, the oil palm is the largest producer of edible oil per unit area. This implies that in order to produce the same volume of oil, the oil palm requires less land compared to all other oil crops. Nonetheless, only about 10 % of the oil palm produces the oil (palm oil and palm kernel oil) whilst the remaining 90 % is mainly the biomass normally

¹ FFB are ripe for harvesting between 24 and 60 months depending on the type of breeding used during nursery. Genetically modified palm seeds for plantation are able to mature much faster and produce more fruits compared to the normal ones.

² The oil palm is able to produce about 3.66 tonnes oil/ha/yr compared to those for rapeseed, sunflower and soybean at 0.6, 0.46 and 0.36 tons oil/ha/yr respectively (Yusoff 2006; Schmidt 2007).

considered as wastes which comprises the empty fruit bunches, fronds, trunks, kernel shells, mill effluent, etc.

On annual basis, the oil palm tree produces averagely 12 bunches of the fresh fruit which weighs about 15–25 kg/bunch of about 1000–1300 fruitlets/bunch depending on the plantation management practices employed. One hectare of oil palm plantation could equally yield close to 148 palm trees (Schmidt 2007) amounting to about 54 tonnes of fresh fruit bunches (FFB).

A FFB consists of about 25–26 % mesocarp oil, 20–22 % kernel nuts, 9–10 % kernel shells, 28–30 % palm empty fruit bunches (EFB), 14–16 % mesocarp fibre (Corley and Tinker 2003; Møller et al. 2000). According to various researches (Corley and Tinker 2003; Goh et al. 2002; Mohd. Din et al. 2005; Soh et al. 2003) the oil palm has potential yield of about 6.8–29 tonnes of oil per hectare of cultivated land (with an average yield of 17 ton oil/ha) depending on the type of plant breeding used. Figure 3.3 shows the hectares of land of cultivated oil crops which correspond to the amount of oil produced from that area of cultivated land.

Other crucial factors that affect the productivity of the oil palm include the type of site selected, the kind and quantities of planting material for the cultivation as well as the agronomy and plantation management practices used (Kee and Goh 2006). Davidson (1993) reported that fertilizer management alone contributes about 29 % increment in oil palm yield. These factors do not only affect the productivity of the oil palm but also the profitability and sustainability as well. The common fertilizers applied in the oil palm plantation are muriate of potash, kieserite, rock phosphate, ammonium sulfate, etc., which are mostly transported to the field and applied manually to the crops. Insects and weeds are also controlled with the application of phosphorus-based or organophosphorus insecticides.

The oil palm industry now focuses on other means of improving its oil yield as well as the plants' tolerance to diseases and genetic ways of prolonging its

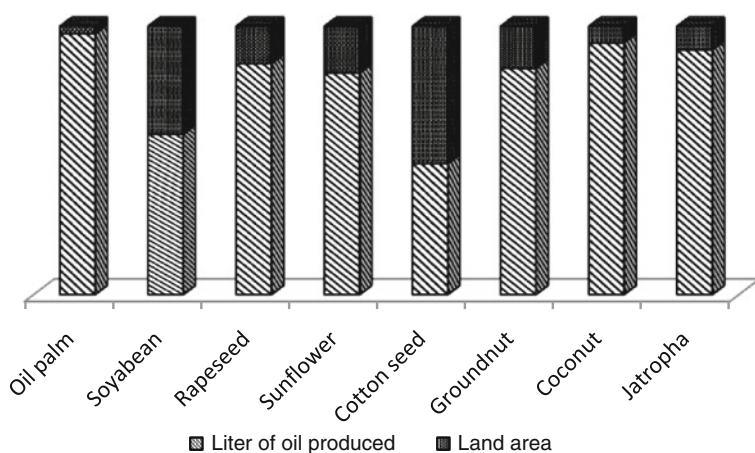


Fig. 3.3 Oil palm efficiency compared to other major oil crops

economic cropping cycle. Ravigadevi et al. (2002) have field tested transgenically high oleic acid palms which were proven to be of high productivity. Though presently the oil palm industry has not yet commercialized genetically bred oil palms, they are believed to be possibly implemented in the next 15–40 years (Corley and Lee 1992; Pushparajah 2002).

3.4 Biofuel Feedstocks from Oil Palm Biomass: Characterization and Availability

3.4.1 First Generation Palm Biofuel Feedstocks

3.4.1.1 Oil Palm Mesocarp Oil

Oil palm mesocarp oil, commonly called palm oil is the red-colored edible oil obtained from the mesocarp of the oil palm fruits after pressing the mesocarp fibers (Reeves and Weihrauch 1979). In its virgin form, the oil is bright orange-red due to the high content of carotenes. Palm oil may be characterized as crude palm oil (CPO) or refined palm oil (RPO) depending on its properties as a result of the processes the raw oil had gone through. CPO contains about 50 % saturated (solid) and 50 % (about 40 % monounsaturated and 10 % polyunsaturated fats) unsaturated fatty acids (liquid). CPO mainly contains glycerides (i.e., mono-, di-, and triglycerides) as well as impurities such as fibers, nut shells, water, free fatty acids (FFA), phospholipids, phytochemicals, trace metals, etc., which must be removed or reduced to an acceptable level in order to make them edible and also appropriate for efficient biofuel production. Phytochemicals such as carotenoids, tocopherols, etc., found in CPO are important food supplements which could be isolated before the refining process in order to render the production processes sustainable. However, FFA in the CPO are nuisance to biofuel production especially when they are in high quantities thus they may need additional pretreatment to reduce the FFA content. CPO is therefore purified with appropriate processes to produce refined, bleached and deodorized (RBD) palm oil in order to remove the FFA and other impurities. The Palm Oil Refiners Association of Malaysia (PORAM) standard specifications for FFA contents are 5 and 1 % maximum for CPO and RPO, respectively. Generally, the FFA of CPO of about 0.51 wt % is lower compared to that for *J. curcas* oil, waste cooking oil and karanja oil whose FFA contents are 1.17, 2.72 and 8.27 wt %, respectively (de Almeida et al. 2002; Salmiah 2000; Bonnie and Mohtar 2009). High FFA feedstocks whose FFA content is above 0.5 wt % like CPO need to undergo esterification reaction before use in engines and this may increase the cost of biofuel production.

Palm oil possesses lower moisture content (about 0.01–0.5 wt %) compared to most vegetable oils that are used for biofuels. However, the high kinematic viscosity of palm oil does not make it appropriate for direct use in engines. Yet,

compared to other oils like beef tallow, neem oil, tung, and castor oil, palm oil's viscosity is better. Palm oil is also found to have the lowest unsaponifiable matter³ content of about 0.03 wt % compared to other oils. According to ASTM D 6751 specifications, sulfur, phosphorus, calcium, and magnesium contents in biodiesel should not exceed 15 ppm, 10 ppm and 5 ppm (for both calcium and magnesium), respectively. Palm oil is among the first five common biofuel feedstocks whose sulfur contents are very low (≤ 1.0 ppm). The phosphorus, calcium, and magnesium contents of CPO are 7.3, 1.1 and 0.5 ppm, respectively. These properties make palm oil highly suitable for use as direct or hydrogenated biofuel in slightly modified diesel engines or as feedstock for biofuel production.

CPO is semi-solid at room temperature due to its comfortable saturation level. It possesses a very high resistance to oxidation and heat at prolonged elevated temperatures. RBD palm oil is semi-solid at room temperature with melting point of about 33–39 °C (Table 3.1). CPO is normally fractionated and crystallized to obtain solid and liquid products called palm olein and palm stearin, respectively.

Palm olein is a monosaturated fat with lower levels of glycerides which is mostly used for frying due to its high thermal stability. The viscosity and glyceride contents in palm olein are lesser than those found in CPO hence much suitable for use directly in diesel engines with or without modifications. The current applications of palm olein and palm stearin are basically for cooking and use as shortenings in bakery, respectively. However, in Malaysia for instance, palm olein and palm stearin are among the major feedstocks used for biofuel production. Figure 3.4 shows the global share of feedstock types used for palm biodiesel production in 2010.

3.4.1.2 Palm Kernel Oil

Palm kernel oil (PKO) is the edible oil mostly dark yellowish in color which is derived from the kernel of the oil palm fruit. At temperatures between 15 and 20 °C, it is typically solid and because it has high oxidative stability, it can withstand high temperatures. Compared to CPO, PKO contains more saturated fats (about 80 % saturated fat with lauric acid, myristic acid, and palmitic acid being major contributors). The remaining 20 % are unsaturated fat (about 17 % monounsaturated and 3 % polyunsaturated fats) with oleic acid being the major composition. Palm kernel olein and palm kernel stearin are the liquid and solid products obtained during the fractionation of PKO, respectively. Certain characteristics of PKO often do not make them suitable for biofuel production. However,

³ Unsaponifiable matter consists of organic compounds like sterols, pigments, waxes, hydrocarbons, etc., which do not react with base to form soaps but remain in the biodiesel after the transesterification reaction because they are nonpolar. High unsaponifiable matter presents the oil not very suitable for biodiesel production. Those oils may require additional pretreatments to remove the unwanted compounds which may eventually increase the production cost of the biofuel.

Table 3.1 Physical and chemical characteristics of liquid products (as biofuel feedstocks) from the oil palm fruits

Characteristic	CPO	RBDPO	PKO	PFAD
Kinematic viscosity @ 40 °C, mm ² /s	44.79	40.9	115.55	80.0–125.0
Moisture content, %	0.01–0.5	<0.1	0.1–0.5	0.03–0.24
Heat capacity @25 °C, kJ/kg °C	1.86–2.20	1.9–2.5	–	–
Conductivity @25 °C, W/m °C	0.1721	–	–	–
Density @25 °C, kg/m ³	885.0–887.5	880.0–910.0	886.0	864.0–888.0
Specific gravity @ 25 °C	0.915–0.922	0.911–0.918	0.918	0.86–0.90
Saponification value, mg KOH/g	196–209	209	245.0–287.5	200.3–215.4
Iodine value (I ₂ /100 g)	48–58	50.1–54.9	14–22	51.2–57.6
Melting point, °C	42–45	33.0–39.0	24–26	40–45
Calorific value (average), MJ/kg	40.1	37.6	35.56	36.01
Fatty acids (%)	–	–	–	–
Caproic (C6:0)	–	–	0.3–0.35	–
Caprylic (C8:0)	–	0.034	3.0–5.0	–
Capric (C10:0)	–	–	3.0–7.0	–
Lauric (C12:0)	–	0.1–0.4	40.0–52.0	0.1–0.3
Myristic (C14:0)	0.5–2.0	0.9–1.4	14.0–18.0	0.9–1.5
Palmitic (C16:0)	32.0–45.0	40.0–47.5	7.0–9.0	42.9–51.5
Palmitoleic (C16:1)	0.1–0.7	0.0–0.6	–	–
Stearic (C18:0)	2.0–7.0	0.3–4.8	1.0–3.0	4.1–4.9
Oleic (C18:1)	38.0–52.0	36.4–44.0	11.0–19.0	32.8–39.8
Linolenic (C18:2)	–	0.3–11.6	2.5–2.7	8.6–11.3
Linoleic (C18:3)	5.0–11.0	0.1–0.5	0.5–2.5	0.2–0.6
Arachidic (C20:0)	0.161	0.356	Trace	–
Beheric (C22:0)	0.061	0.059	–	–
Tricosanoic (C23:0)	0.031	0.022	0.6–0.65	–
Lignoceric (C24:0)	0.066	0.067	–	–
FFA (wt % as palmitic)	0.51	0.1	4.5–5.0	72.7–92.9

Source de Almeida et al. (2002), Razmah and Salmiah (2004), Bonnie and Mohtar (2009), Hamirin (1983)

they are cost-effective feedstock for biodiesel production and their successes for biofuel production have been demonstrated by various researches (Alamu et al. 2007; Ojolo et al. 2011). Palm kernel olein is the liquid fraction from palm kernel oil fractionation and crystallization processes and it is best used as frying oil with limited use in diesel engines or as feedstock for biofuel production though it is highly suitable for biofuel production. Table 3.1 shows the physical and chemical characteristics of palm oil.

3.4.1.3 First Generation Oil Palm Biofuel Feedstocks: Global Profile

CPO is currently the largest produced edible oil in the world and it forms approximately 35 % of the global oil supply (Schmidt 2007; Hartley 1988) with about 12 countries being major contributors. In 2010, out of about 163 million tons of oil and

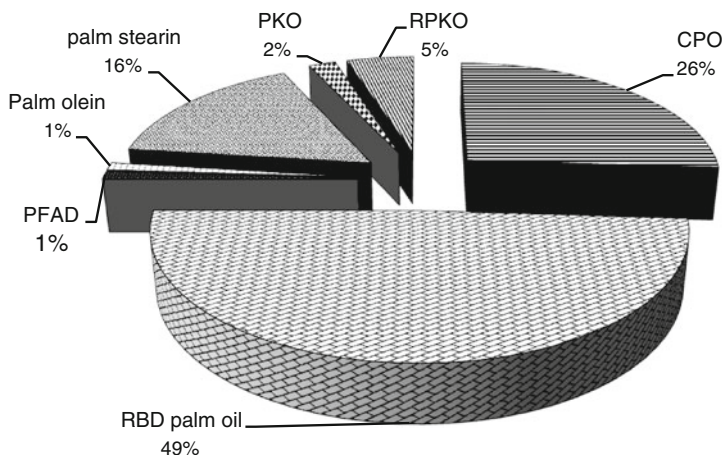


Fig. 3.4 Contribution of first generation liquid feedstocks from oil palm biomass to the global palm biodiesel production in 2010

fats produced in the world, CPO and PKO together dominated in shares with about 27 % followed by soybean oil (MPOB 2012). In 2011, for a total of about 68.2 million tons of vegetable oils and fats that were exported throughout the world, CPO and PKO together accounted for nearly 90 % which implies that palm oil holds impressive market on the international oils and fats arena (MPOB 2012). For this amount exported, Malaysia's export dominated with about 45 % share. Palm oil and palm kernel oil are the cheapest and most consumed edible oil (Lam et al. 2009) that are sold at relatively low discount compared to soybean oil and they have been able to sustain the world with great contribution to edible fats and oils. Figure 3.5 shows the price trend of the commonly used oils for biofuels in the world.

The constant growing demand for palm oil is mainly due to its relatively cheaper price and its dynamic applications for both edible and nonedible products. Its sustainability in terms of supply may highly depend on the yield improvements achieved by the Malaysian and Indonesian oil palm industries (Carter et al. 2007).

In 2011, out of the 166.2 million tons of vegetable oil produced in the world, palm oil contributed about 56.9 million tons (~ 34 % of total production) (MPOB 2012). However, the total cultivated land was about 5 % of the world's total vegetable oil crops' cultivated area which implies that the oil palm is highly productive. In 2010, Malaysia and Indonesia together contributed the highest share (~ 85 %) of the total palm oil production in the world with about 21.5 million tons and 24.8 million tons, respectively (OECD-FAO 2011). This data is projected to increase by about 11 % by the end of 2013. Malaysia's oil palm cultivated land area of about 32 million hectares forming about 12.5 % of its total landmass is presently recognized as the world's largest producer of Certified Sustainable Palm Oil (CSPO) contributing over 50 % of total CSPO production (OECD-FAO 2011). In Africa, Nigeria remains the largest producer of palm oil and the world's fourth

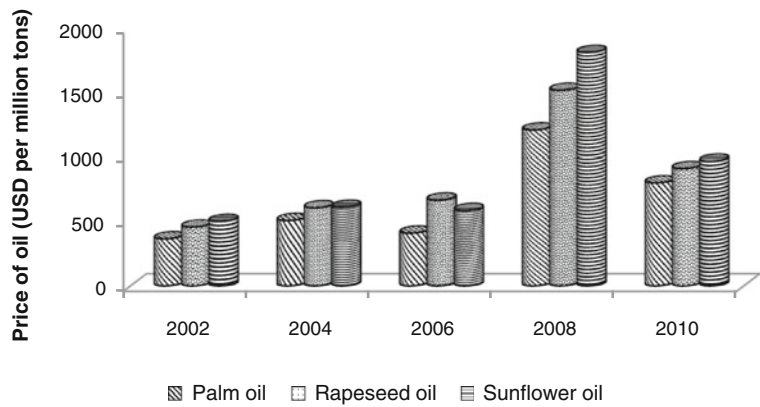


Fig. 3.5 Comparison of the prices of CPO and the two commonly used edible oils for biofuel production in the world (OECD-FAO 2011)

leading producer with a total oil palm landmass of about 385,000 ha (RSPO report 2006). Figure 3.6 shows the 2011 production capacities of the first five leading palm oil producing countries in the world (MBOP 2012).

From 2005 to 2009, CPO production and consumption grew at compound annual growth rates of 7.9 and 8.6 %, respectively (OECD-FAO 2011). Figure 3.7 shows the production and consumption trend of CPO and CPKO in the world in 2012 (MPOB 2012).

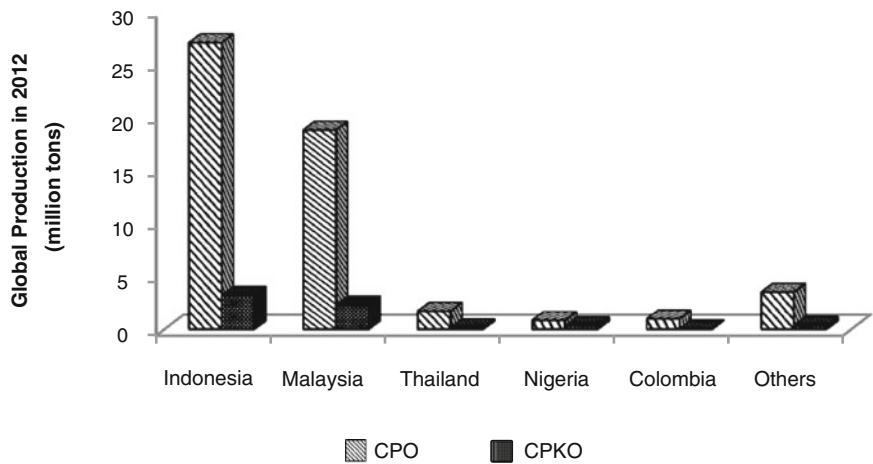


Fig. 3.6 Share of oil palm production in the world by major contributing countries in 2011. ('Others' mainly include Papua N. Guinea, Ecuador, Cote d'Ivoire, Cameroon, Honduras, Costa Rica as well as few others with minimal contributions)

3.4.2 Second Generation Palm Biofuel Feedstocks

3.4.2.1 Palm Fatty Acid Distillate

Palm Fatty Acid Distillate (PFAD) is a by-product obtained as a distillate from the fatty acid stripping and deodorization of CPO during the physical refining process. It is a highly odoriferous brown solid fat at room temperature and melts easily upon heating. PFAD contains high contents of fatty acids (Table 3.1) as well as glycerol esters (Ab Gapor 2010). PFAD presents a potential low cost second generation feedstock for palm biofuel production as it is mostly used as a source of fatty acid for non-food applications in industries. It has also been used as a green substitutes for fuels in boilers and engines for power production.

PFAD has FFA content of about 80–90 % mostly in the form of palmitic acid. However, PFAD has significantly higher content of unsaponifiable matter in the range of 1.1–2.3 % (Bonnie and Mohtar 2009). Other constituents of PFAD include about 14 % glycerides, 0.8 % squalene, 0.5 % vitamin E, 0.4 % sterols and 2.2 % other extractives (Bonnie and Mohtar 2009; Hamirin 1983). Biofuel production from PFAD has gained recent interest due to the cheaper price of PFAD compared to CPO and RBD palm oil. For instance, in 2008, PFAD price on the international market was about USD 711/ton compared to about USD 1021/ton for RBD palm oil (Bonnie and Mohtar 2009). These prices were reduced in 2010 to about USD 648/ton and USD 812/ton for PFAD and RBD palm oil, respectively (MPOB 2012). Again, the utilization of PFAD for biofuels and other value-added palm bioproducts may improve the economic viability of the oil palm industry for sustainable development.

In Malaysia, about 0.63, 0.71 and 0.77 million tons of PFAD were produced as by-products in 2006, 2008 and 2010, respectively (Ab Gapor 2010; MPOB 2012). In 2011, about 2.05 million tons of PFAD were produced in the world. These data shows significant availability of PFAD for sustainable palm biofuel production.

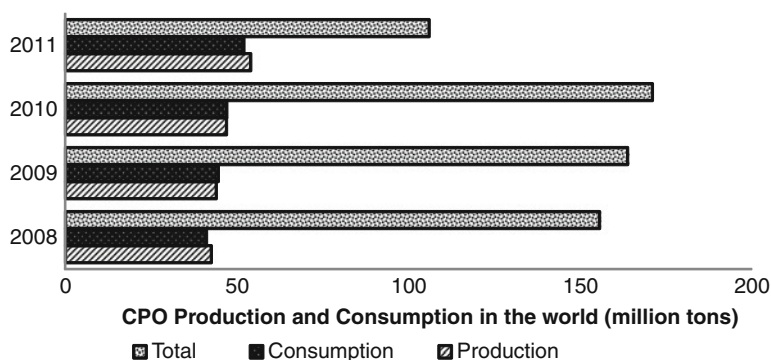


Fig. 3.7 Global CPO production and consumption trends from 2008 to 2011

3.4.2.2 Palm Oil Mill Effluent

Palm oil mill effluent (POME) is a thick concentrated dark brownish colloidal slurry which is the by-product from the palm oil milling process. POME is the largest amount of liquid wastes that is generated constantly from the oil palm mills. POME basically consists of water ($\sim 95\%$), residual oil ($\sim 4\%$) with FFA of 30–70 % and suspended solid materials (~ 1) and in its untreated form they are highly odoriferous. The three major unit processes that generate POME in the palm oil mill are (1) the sterilization of FFB which discharges the sterilizer condensate mostly water and organic solids (2) the clarification of the pressed oil which generates water and traces of oil (3) the hydrocyclone separation of the cracked mixture of palm kernels and PKS. POME generated from the sterilization process of FFB and the clarification process of the extracted CPO contributes about 36 and 60 % of the total POME generated within the oil mill, respectively. The hydrocyclone separation of the cracked mixture of kernel and shells also contribute about 4 % of the total amount of POME generated by the oil mill (Sethupathi 2004).

With about 1.5 m^3 (about 1.5 tons) of water used in the processing 1 ton of FFB, about half of this quantity (approximately 0.50–0.75 tons water) comes out as POME (Alam et al. 2009). For instance, in 2004, about 40 million tons of POME was generated from about 372 palm oil mills in Malaysia (Yacob et al. 2005). This figure rose drastically to about 53.1 million tons in 2006. Generally, for every ton of CPO produced, about 3.25 tons of POME is generated (Corley and Tinker 2003). Globally, over 90 million tons of POME are produced every year.

Table 3.2 shows the chemical compositions of POME. Depending on the type of FFB, method and efficiency of CPO extraction from FFB, POME may contain cellulosic materials that basically form its total solid content (Ma and Yusoff 2005). Due to the continuous heat generation during the sterilization of FFB and other mechanical processes within the palm oil mill, the POME discharged would have temperatures ranging from 80 to 90 °C (Ma and Yusoff 2005). Because POME has high biological oxygen demand (BOD) and chemical oxygen demand (COD), they are considered more polluting than domestic sewage and must be treated before discharge into the environment (Ma and Yusoff 2005).

The nutritive contents of POME have also been reported by Hamirin (1983) and with the high protein (9.6 % dry matter), fatty acids ($>50\text{ mg/g}$ dry weight), carbohydrate, and nitrogen contents in POME, it can be transformed into other useful products using microbial processes (Ma 1999). POME contains about 11 % cellulose, 7 % hemicellulose, and 42 % lignin on dry basis (O-Thong et al. 2012). The mineral contents of POME show that they are high potential sources of fertilizers for improved plant growth. Composts and fertilizers prepared from chicken manure and sawdust have low aluminium content (Muhrizal et al. 2006) but high lead content (Habib et al. 1997) compared to POME.

Depending on the amount of water used to process FFB into CPO, the physico-chemical characteristics of POME may differ. For efficient water consumption in

Table 3.2 Physical and chemical characteristics of POME

Parameter	Value	Limit of discharge
pH	3.8–4.7	5.0–9.0
Temperature, °C	80–90	45
Total solids, mg/l	40,000–75,000	–
BOD, 30 °C, mg/l	23,000–69,215	100
COD, mg/l	42,500–112,023	NDL
Suspended solids, mg/l	16,500–47,140	400
Total volatile solids, mg/l	34,000	NDL
Ammoniacal-Nitrogen, mg/l	35–112	150
Total nitrogen, mg/l	50–1493	200
Phosphorus, mg/l	180	–
Zinc, mg/l	2.3	–
Copper, mg/l	0.89	–
Boron, mg/l	7.6	–
Potassium, mg/l	2,270	–
Magnesium, mg/l	615	–
Calcium, mg/l	439	–
Iron, mg/l	46.5	–
Manganese, mg/l	2.0	–
Oil, mg/l	4000–10,052	50

Source Choorit and Wisarnwan (2007), Najafpour et al. (2006), Ma and Yusoff (2005), Ma (1999), Laws of Malaysia (2003) (NDL No discharge limit after 1984)

the mill, small amount of water could be used to process the FFB and the resulting POME would contain high organic matter contents.

3.4.2.3 Oil Palm Leaves

OPLs are leaflets of pinnate-shapes of about 3–4 m in length that are attached to the petioles of the OPF. OPLs consist of spines that are arranged on two lateral planes. OPL is composed of three parts namely the blade, the petiole, and the base (Dransfield et al. 2008). An averagely matured oil palm tree generates about 20–25 kg of leaflets annually which are not utilized on commercial basis but mostly used as much in the plantation. As the age of the oil palm tree increases, the ratio of lengths of the OPL to OPF petioles decreases (Dransfield et al. 2008). For example, a 6-year-old oil palm tree has the ratio of OPL/OPF to be about 1.7 compared to 0.3 for a 21-year-old tree. This implies that the leaves of an older tree may have higher nutritional value compared to that of the petioles of the OPF (Dahlan et al. 2000).

The nutritive values of OPLs are higher compared to those for OPF. They contain about 13 % crude protein, more than 4 % fat (Aim-ueb et al. 2008), 3.8 % DM silica (Dahlan et al. 2000), about 60–68 % holocellulose and 14 % glucose (Abdul Khalil et al. 2006). OPL is found to contain more cellulose (35 %)

compared to that of neem tree (30 %), and close to the same amount in wood (40–45 %). The cell wall of the OPL contains moderate amount of crystalline cellulose mainly polysaccharides in the form of acetylated arabinoxylans (Abdul Khalil et al. 2006). The mineral contents of OPL as reported by Abdul Khalil et al. (2006) are about 2.62 % nitrogen, 0.16 % phosphorus, 1.25 % potassium, 0.24 % magnesium, 0.6 % calcium, 0.55 % chlorine, and 0.22 % sulfur. The vitamins A and E contents of OPL range from 1900 ppm and 11229–14805 µg/g, respectively. These chemical characteristics of the OPL suggest a better option of its transformation into value-added products such as sugar for bioethanol as well as phytochemicals. However, after harvesting of the FFB, the OPLs are usually left in the plantation together with the OPF for only nutrient recycling.

3.4.2.4 Oil Palm Fronds

OPFs comprise the petiole (about 6–8 m long) and the rachis (about 1–2 m long) which bears about 250–350 leaflets at a time. OPFs are generated in the oil palm plantation after field management and harvesting and are mostly left to rot in the plantation for nutrient recycle due to their high nutritive values (Yusoff 2006). OPFs contain about 5–12 % crude protein and 2 % fat (high in unsaturated fatty acids) (Hassim et al. 2010). The total amino acid in OPF is about 174–175 µg/g comprising about 22–23 µg/g glutamic acid, 110–111 µg/g serine, and 27.0–27.5 µg/g proline (Zahari et al. 2012). OPFs with moisture content of about 10.26 %, contain about 0.2–0.4 % sulfur, 0.2–2.3 % potassium, 0.2–0.5 % magnesium, 0.02 % phosphorus, 1.4–2.9 % calcium, 2–4 ppm boron, 2–61 ppm manganese, 2 ppm copper, 3–9 ppm zinc and 66–100 ppm iron (Zahari et al. 2012).

The petiole of the OPF contains the fiber (mainly lignocellulosic materials) covered with a hard epicarp. The lignin, cellulose, and hemicellulose contents in OPF are about 16.96, 46.19, and 34.26 %, respectively, with ash content of about 11.36 % (Aim-oeb et al. 2008; Khamseekhiew et al. 2001). The high holocellulose content (cellulose and hemicellulose) of OPFs make then high sugar containing biomass with about 40.56 % glucose and 17.40 % xylose that are convertible to bioethanol and other value-added bioproducts like xylitol (see Appendix G). Other sugars in OPF include sucrose (20.46 g/l) and fructose (1.68 g/l) (Zahari et al. 2012). OPFs are reported to contain higher holocellulose (about 80 % dry matter content comprising cellulose and hemicelluloses) compared to the fibres of pineapple leaves, coconut leaves, and banana stem (Abdul Khalil et al. 2006). The acid detergent fiber (ADF) and neutral detergent fiber (NDF) of the OPFs are found to be about 45.5 % dry matter and 67.6 % dry matter, respectively (Khamseekhiew et al. 2001). The carotenoids and tocopherols contents of OPFs have been reported to be about 240–320 ppm and 340–350 ppm respectively (Ofori-Boateng and Lee 2013a, b). The water and ethanolic extractives have been reported by Goh et al. (2010) to be about 5.12 and 5.84 % dry weight of OPF (Goh et al. 2010).

OPF form the largest group of OPW (in the form of solid residue) whose total global generation capacity in 2011 amounted to nearly 92.4 million tons (dry weight)

annually (OECD-FAO 2011). The oil palm industries in Malaysia generated about 54.17 million tons and 54.24 million tons of OPF in 2010 and 2011, respectively (Wan Zahari et al. 2004). The increment in OPF generation as wastes in Malaysia from 2004 to 2011 was about 19 million tons (Wan Zahari et al. 2004) and this amount is projected to increase to about 58 million tons by 2020 (MPOB 2012).

3.4.2.5 Oil Palm Trunk

During every replanting of oil palm trees (mostly after 25 years of planting), large amount of OPF are generated from the old oil palm trees that are cut down for replacement. A felled OPT has a bole length of 7–13 m with a diameter of 45–65 cm taken at breast height (Abdul Khalil et al. 2010). After every replanting of oil palm trees throughout the year, approximately 37 million tons of OPT are generated in Malaysia (Yusoff 2006). Out of this amount, only about 40 % are used for plywood and other furniture applications. The remaining 60 % that are discarded as wastes are mostly in the form of core-logs (50 %) and veneers off-cuts (10 %) (Abdul Khalil et al. 2010).

The OPT comprises long vascular bundles which are surrounded by parenchyma tissues consisting of numerous fibrous strands and vascular bundles. About 53.87 % (dry weight) of OPT constitutes extractable fiber bundles while the bark and parenchyma tissues form about 14 and 32 % of the dry weight of the OPT, respectively (Abdul Khalil et al. 2010). These cells and tissues of the OPTs are packed with high amounts of holocellulose (about 45 % cellulose and 25 % hemicellulose), lignin (about 18 %), and other extractives (about 10 %) which can be fractionated, isolated, and purified for value-added bioproducts like biofuels (see Appendix G). The sugar contents in OPT are about 35–48 % glucose, 11–16 % xylose, 0.50–0.63 % galactose, 1.00–1.37 % arabinose, 0.50–0.95 % mannose, and 0.20–0.23 % rhamnose (Halimahton and Abdul 1990).

Other chemical constituents of OPT includes fatty acid (<2 %), 3 % crude protein, 43.80 % carbon, 6.20 % hydrogen, 0.44 % nitrogen, 42.65 % oxygen, 0.09 % sulfur, and 6.87 % ash (all in dry weights basis). OPT has an average density of 370 kg/m³, moisture content of 55–83 % and heating value of 19.26 MJ/kg (Nipattummakul et al. 2012).

Malaysia's oil palm industry generated a total of 13.5 million tons of OPT in 2011, and this is projected to increase by 50 % by the year 2020 (MPOB 2012).

3.4.2.6 Oil Palm Roots

The OPRs consist of fibrous (or adventitious) root system with many tiny moderately branched non-woody roots that are growing from the base of the OPT. The primary roots of the OPR system are of constant diameter and they emerge independently and periodically from an area at or near the base of the OPT called the root initiation zone (Dransfield et al. 2008). OPR are usually isolated from the

palm tree during replanting by using an excavator or a stump grinder and they are mostly left in the plantation to rot without proper utilization or dumped at landfills. OPRs are the least utilized form of oil palm biomass though their chemical characteristics may be better than most other biomass.

The OPR forms about 12 % the total mass of the OPT at full maturity. Normally, OPT are not felled together with the root system hence OPR have not gained much attention for value-added products. However, the chemical characteristics of OPR show the presence of high amount of sugar or carbohydrate close to that of OPF with higher contents of extractives.

3.4.2.7 Empty Fruit Bunches

EFB is a non-wood lignocellulosic biomass which forms about 23 % of the total mass (or weight) of the FFB (Schmidt 2007). EFB is the largest amount of solid wastes that are generated from the palm oil mill during the stripping process of the fresh palm fruits from the FFB. EFB physically consists of a main stalk (forming about 20–25 % of the total weight of EFB) and numerous spikelets (forming about 75–80 % of the total weight of the EFB) with sharp spines at their tips (Ahmad et al. 2009). The production of 1 ton of CPO generates nearly 1.3 tons of EFB. Globally, about 42.3 million tons of EFB are generated by the oil palm industry annually (Kelly-Yong et al. 2007; Ahmad et al. 2009) in which only an insignificant amount is utilized as nutrients in the oil palm plantation because of their high nutritive values. Due to their high moisture contents of about 55–56 % by wet weight (Mohammed et al. 2012), they are hardly utilized by the palm oil mills as boiler fuels. EFBs contain about 3.45 % ash, 8.97 % fixed carbon, 82.58 % volatile matter, 46.62 % carbon, 6.45 % hydrogen, 1.21 % nitrogen, 0.035 % sulfur, 0.18 % magnesium, 0.06 % phosphorus, and 45.66 % oxygen (Elbersen et al. 2005; Mohammed et al. 2012).

EFB vascular strands contain about 41.3–46.5 % cellulose, 25.3–33.8 % hemicellulose, and 27.6–32.5 % lignin (Sudiyani 2009; Piarpuzán et al. 2011). EFB sugar contents are about 2.5 % galactose and 33.1 % glucose (Abdul Khalil et al. 2006). The fatty acid content in EFB is less than 2 % with its extractives and crude protein also constituting approximately 7.8 % and 1–3.8 %, respectively. Though the calorific value of EFB is between 17 and 19 MJ/kg (Ma and Yusoff 2005; Mohammed et al. 2012), a value slightly lower (due to high moisture and oxygen contents) than that for wood and coal (Demirbas 2004; Yang et al. 2006), it serves as a potential source of biofuel.

The inorganic contents (expressed in % ash, moisture free) of EFB have been analyzed by Lahijani and Zainal (2011), Omar et al. (2011) and Mohammed et al. (2012) to consist of Si_2O (10.83–27.0), K_2O (34.7–53.73), CaO (1.9–12.5), MgO (4.8–8.75), Cl (3.6–5.3), Fe_2O_3 (1.28–3.6), Al_2O_3 (0.46–1.22), Na_2O (0.55–1.54), and P_2O_5 (1.12–3.6). EFB fuel density is about 1420 kg/m³ (Mohammed et al. 2012).

3.4.2.8 Palm Pressed Fiber

Malaysia being the current world's leading exporter of palm oil generates about 12 million tonnes of Palm Pressed Fiber (PPF) annually (Lau et al. 2008; Mazaheri et al. 2010). For every ton of oil palm fresh fruits processed, about 0.16 tons results in PPF. PPF is an elongated fibrous solid residue which are obtained from the oil palm fruits and are generated after the oil extraction processes. The strands of PPF which are about 30–50 mm in length contain about 5–7 % residue oil after the screw-press extraction of CPO (Choo et al. 1996; Sanagi et al. 2005). As the palm oil milling does not involve any chemical process which utilizes toxic substances, PPF is considered organic and could be mixed with other nutritious substances for the manufacture of edible products like fiber bread as they contain significant amounts of phytochemicals. In the oil mill, due to the porous nature of PPFs, they are mostly used as economically viable renewable fuels for boilers for steam and electricity generation (Yusoff 2006). PPF has low moisture content (35 % moisture content by wet weight) compared to EFB (about 55.5 % wet weight) thus highly preferable for use as boiler fuels (Azali et al. 2005). The chemical and physical characteristics of PPF make them useful materials for sustainable production of various palm value-added bioproducts such as biofertilizers, bio-oils, etc. (see Appendix G).

PPFs strand basically has a diameter of 150–500 μm (Sreekala and Thomas 2003; Bismarck et al. 2005), density of 0.7–1.55 g/cm^3 (Sreekala and Thomas 2003), tensile strain of 13.71 %, tensile strength of 50–400 Mpa, cell wall thickness of 3.38 μm , fiber coarseness of 1.37 mg/m , and rigidity index of 55.43×10^{-4} (Sreekala et al. 1997).

PPF contains about 39 % fatty acid, 75.99 % volatile matter, 12.39 % fixed carbon, 5.33 % ash, 50.27 % carbon, 7.07 % hydrogen, 0.42 % nitrogen, 0.63 % sulfur, and 36.28 % oxygen (Azali et al. 2005). The heating value of PPF is about 20.64 MJ/kg. Considering sugar contents on dry basis, PPF consists of about 41–61 % alpha cellulose, 42–65 % cellulose, 17–34 % hemicellulose, 13–25 % lignin, 18–21 % pentosan, 1.3 % mannose, 2.5 % arabinose, 33.1 % xylose, 1.0 % galactose, 66.4 % glucose (Law et al. 2007; Abdul Khalil et al. 2008; Rozman et al. 2007). About 2.8–15 % extractives can be obtained from PPF with 4000–6000 ppm of vitamin A and 2400–3500 ppm of vitamin E (Choo et al. 1996). The inorganic composition of PPF expressed in % ash (moisture free) include 3.54 % Si_2O , 0.24 % K_2O , 1.15 % CaO , 0.13 % MgO , 0.24 % Fe_2O_3 , 0.57 % Al_2O_3 , and 0.19 % P_2O_5 (Chaiyaomporn and Chavalparit 2010). PPF fuel density is about 1400 kg/m^3 (Mohammed et al. 2012).

3.4.2.9 Palm Kernel Shells

The shells obtained after cracking the palm kernel seeds are called Palm Kernel Shells (PKS). PKS can be described as the hard endocarps surrounding the palm kernels or seeds which are obtained after the residual nuts from the screw press are

mechanically crashed to extract the seeds or kernels. PKS are considered organic pellets and high grade solid biofuels that can serve same purpose as coal which can be used as fuel by boilers, furnaces, foundaries, brick kilns, etc. They are always available in large quantities annually but have limited uses now as they are mostly dumped at landfills.

Presently due to increase in palm oil production, the world's annual generation of PKS is estimated at 11.1 million tons as compared to 2.52 million tons and 4.3 million tons in 2004 and 2006, respectively (MPOB 2012). Because PKS possess high calorific value of about 22.14 MJ/kg, low sulfur of about 0.09 % dry weight and low ash of about 3 % dry weight, they are often used as fuel for the power plants in the oil palm industry (Yusoff 2006). However, nearly 30 % of these wastes are utilized by the oil mill for power generation; the rest have limited commercial applications especially for biofuels production.

The proximate and ultimate compositional analyses carried out by Chaiyaomporn and Chavalparit (2010) show that PKS contains about 30 % moisture content by wet weight, 73.74 % volatile matter, 18.37 % fixed carbon, 2.21 % ash, 53.78 % carbon, 7.20 % hydrogen, and 36.30 % oxygen. The inorganic compositions of PKS expressed in % ash (moisture free) include 2.96 % Si_2O , 0.60 % K_2O , 0.48 % CaO , 0.83 % MgO , 0.08 % Fe_2O_3 , 0.24 % Al_2O_3 , and 0.59 % P_2O_5 (Chaiyaomporn and Chavalparit 2010). The fuel density of PKS is about 1430 kg/m³ (Mohammed et al. 2012).

The holocellulose compositions of PKS are about 20.8 % cellulose and 22.7 % hemicellulose with lignin content of about 50.7 % (Saka 2005). The unique characteristics of PKS present them highly suitable for use as solid biofuels most especially when transformed into pellets. They are often mixed with specific proportions of EFB and used as biomass fuel in the boilers of the palm oil mill.

3.4.2.10 Palm Kernel Cake

Palm Kernel Cake (PKC) is the by-product or solid residue generated from the mechanical screw pressing of palm kernels which contains some residual oil. In Malaysia, approximately 2.2 million tons of PKC were produced in 2007 which increased to about 2.4 million tons in 2009 (MPOB 2012) due to expansion of the oil palm industry. The global generation capacity of PKC in 2011 was estimated at 3.5 million tons (MPOB 2012).

PKC is being used currently as fattening steers in feedlots (Akpan et al. 2005). Depending on the amount of PKS in the PKC, crude protein content of PKC may range from 160.0 to 180 g/kg DM. PKC again contains high amount of minerals including copper and zinc which have no significant disadvantage (such as mortality in ruminants fed with PKC) as reported by Hair-Bejo et al. (1995). PKC contains about 78 % hemicellulose in the form of mannan and 12 % cellulose (Sundu and Dingle 2003).

PKC has dry matter content of 883 g/kg DM, 126–131 g/kg DM extractives, 39.4 g/kg DM ash content, 131 g/kg DM crude fiber, 460.5 g/kg DM ADF and

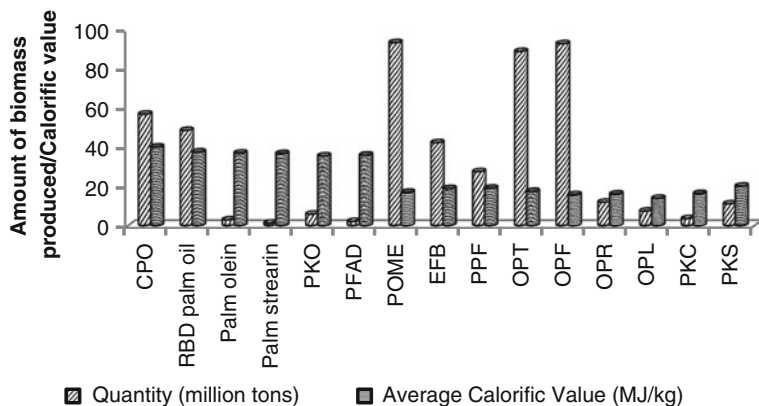


Fig. 3.8 Global generations of oil palm biomass and their corresponding Calorific Values in 2011 (MPOB 2012; Choo et al. 1996)

682 g/kg DM NDF (Ramachandran et al. 2007; Akpan et al. 2005).) PKC contain phytochemicals such as carotenes (0.16 mg/100 g), thiamine (0.07 mg/100 g), riboflavin (0.07 mg/100 g), nitrates (3.05 mg/100 g), and nitrites (0.29 mg/100 g) (Ogbuagu 2008). Figure 3.8 summarizes the annual production and energy contents of oil palm biomass in the world.

3.5 Future of the Oil Palm Industry as the Sole Source of Oil Palm Biomass

The future of every industry for sustainable development is always assured whenever there is continuous flow of raw materials into the system at an economically competitive, socially acceptable, and environmentally benign ways. The oil palm industry is no an exception from this fact especially as it currently stands as the sole generator of oil palm biomass through which the future of palm biofuels also relies. There are various factors which determine the strength of the oil palm industry and these include the expansion of the industry through the cultivation of extra hectares of land in the major producing countries; the potential success of improving the oil yield; and finally, the ability to mechanize (Carter et al. 2007). Other factors such as cost, climate change, and technology advancement would also play an important role in the growth, dynamics, and sustainability of the palm oil industry presently and in the future.

Figure 3.9 shows the cost of various types of oil palm biomass (in Euro per tonne) on the international market in 2006. FFB, EFB and PKS are the cheapest sources of oil palm biomass that can be utilized for biofuels and other value-added bioproducts (see Appendix G). Though RBD palm kernel oil is the most expensive oil palm biomass for biofuel production, on the international oils and fats market,

it is the cheapest. Oil palm biomass as feedstock for biofuels are cost-effective and the production processes for palm biofuels could be efficiently designed to achieve sustainable palm biofuel production.

The Roundtable for Sustainable palm Oil (RSPO) has been established to move the oil palm industry toward a more sustainable production whereby major stakeholders like growers, processors, investors, traders, retailers are brought together to facilitate the growth of the industry. The contributions from research and developmental institutes both private and public are also major instruments in supporting the development and technological innovations to push the oil palm industry forward.

Though Malaysia's oil palm industry is growing slowly, they are able to increase their production yield by about 30 kg every year while Indonesia continues to dominate with its rapid expansion. These two countries are working hard in order to produce more palm oil not only for food but also for biofuel applications (Smith 2006). The Malaysian National Biofuel Policy mandates the increase in the production of quality oil palm biofuel to satisfy the global demands and together with Indonesia, it is forecast to contribute about 6 million tons of palm oil to the world's biofuel industry (Basiron 2008).

One major challenge faced by the industry since its inception has been its large contribution to global warming and other environmental problems. The issues of biodiversity loss, land disputes as well as soil, land, air, and water pollution have been among the negative things that put the oil palm industry under scrutiny worldwide. However, with sustainable indicators and tools set in place for the oil palm industry, these environmental issues as well as social and policy issues would be a thing of the past.

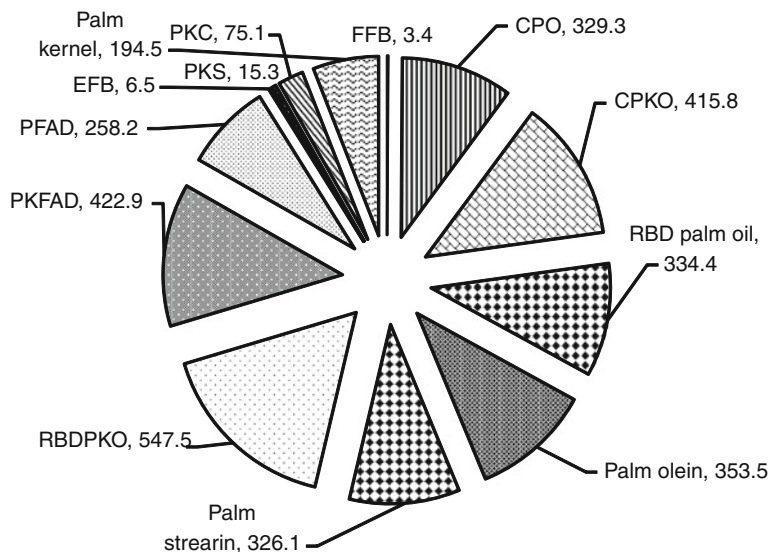


Fig. 3.9 Cost of oil palm biomass (Euro/ton) in 2006 (MPOB 2006)

3.6 Conclusion

The sustainability of palm biofuels production largely depends on the sustainability of the oil palm biomass characteristics and production technologies. The physical and chemical characteristics of all the types of oil palm biomass are reported to be good thus make them highly suitable for the production of all the three kinds of biofuels. Oil palm biomass is assessed to be the cheapest source of biofuel feedstocks in the world. The implementation of sustainable principles set by the RSPO and other similar organizations could make palm biofuels one of the most sustainable biofuels in the world.

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Chapter 4

Production of Palm Biofuels Toward Sustainable Development

Abstract The oil palm presents a comparatively advantageous source of feedstock for biofuels production compared to other first-generation biofuel feedstocks. Among the sources of feedstocks for biofuel production currently available and developed in the world, the oil palm is the prime option which fulfills the sustainability criteria for high productivity, efficiency, competitive price discounts, and above all it is cost effective. Biofuels produced from oil palm biomass would be considered sustainable only when all the production chains from oil palm cultivation to biofuels production (including the production of input materials and energy) are within the acceptable production criteria for sustainable oil palm and biofuels developments. In order for the oil palm industry to fully accomplish the objectives of sustainable oil palm biofuels production, Malaysia and Indonesia are currently ensuring the implementation of stringent sustainability standards via best management practices especially for the production of palm biofuels so as to improve yield and reduce the amount of input resources. This chapter highlights on some best management practices involving globally accepted initiatives for sustainable oil palm agriculture, palm oil milling, and refining as well as different production routes to palm biofuels production. Integration of different production routes for various types of palm biofuels through effective utilization of wastes for sustainable development are also elaborated in this chapter.

Keywords Palm biofuels • Sustainable biofuel production • Sustainable palm biofuel production • Sustainable palm oil • Sustainable palm production • Sustainable development • Sustainability • Integrated biofuel system

4.1 Introduction

Though the production and consumption of oil palm biofuels are found to improve economic development and mitigate against potential impacts of greenhouse gas (GHG) emissions from the transportation and industrial sectors to some extends, their linkage with sustainability is a complex one. For instance, the production of

oil palm biomass (mainly palm fresh fruit bunches (FFB) as major source of palm feedstocks) for biofuels production is found to contribute to biodiversity loss, water, soil, and air pollution as well as food security problems though it still stands as the most productive and efficient oil crop in the world. In fact, among all the oil crops that exist, oil palm is the most versatile in that the tree could produce so many different kinds of biomass, which could be tapped for many value-added bioproducts like biofuels (see Appendix G). However, the positive impacts of oil palm biofuels on sustainability would be achieved when the whole production chains are critically assessed and subsequently planned toward sustainable production and consumption methods. Again, in the process of producing FFB for biofuels production, huge amounts of palm wastes are generated which are also high potential sources of second-generation palm biofuel feedstocks. Integrating the production of these second-generation biofuels into the production system for first-generation palm biofuels would help minimize wastes emissions as well as improving the economic value of the oil palm.

The cultivation of oil palm biomass¹ is a crucial production step in the whole production chain of oil palm biofuels. Presently, the world's focus on sustainable agriculture and biofuel production has urged the oil palm industry in the major producing countries to come out with possible sustainability standards for good production practices.

Though a starting compliment to the oil palm has been the most productive oil plant in the world which highly fits it into the sustainability criteria, greater work is still in progress to meet the world's standard for sustainable agriculture and energy development.

The oil palm biomass as already characterized (see Chap. 3), is an economic source of biofuel if indeed efficient utilization of all the forms (both solid and liquid) is sustainably implemented throughout the life cycle the oil palm tree. During plantation management processes and harvesting of the FFB, large quantities of wastes including oil palm fronds (OPF), oil palm leaves (OPL), oil palm trunks (OPT), and oil palm roots (OPR) (only during replanting) are generated with about 80 % not utilized² on commercial scale (Yusoff 2006). Also, in the palm oil mill, only about 40 % the oil palm biomass (such as empty fruit bunch (EFB), palm pressed mesocarp fiber (PPF), palm oil mill effluent (POME), palm kernel shells (PKS), palm kernel cake (PKC), palm fatty acid distillate (PFAD) etc.) generated as wastes are utilized for the production of biofuels³ in the mills. Generally, about 80 % of the oil palm biomass are not sustainably utilized but dumped at unauthorized

¹ 'Oil palm biomass' in this book refers to both the liquid products and by-products from the processing of FFB (like POME, CPO) and solid residues from the oil palm tree (like FFB, OPF, EFB) after harvesting and processing of FFB.

² Only about 20 % oil palm biomass in the form of solid residues that are generated within the plantation are utilized as nutrients and mulch with a few being used as furniture etc. The remaining 80 % are under-utilized (Yusoff 2006).

³ Only about 40 % of the oil palm biomass generated within the mill like PPF, PKS, EFB are mostly used to fuel the boilers for steam generation while POME is mostly utilized for biogas

places creating environmental problems (Yusoff 2006). However, the abundant availability of oil palm wastes in the oil palm industry has been a major breakthrough for the reduction of fossil fuels consumption and waste emissions from both the plantation and the oil mill which could eventually minimize the cost of crude palm oil (CPO), crude palm kernel oil (CPKO), and palm biofuels at large. The solid residues like EFB, PPF etc. generated in course of the oil extraction processes can also be utilized in a more sustainable way for biofuel production.

Currently, oil palm biomass are used as feedstocks for the production of all the three major types of biofuels (namely liquid, solid, and gaseous biofuels which have been discussed in Chap. 2). The commonly produced and consumed types of liquid palm biofuels include biodiesel, bioalcohols, and bio-oils which are either sourced from first- or second-generation palm feedstocks (see Chap. 3). The common types of bioalcohols produced presently from oil palm biomass in the world are bioethanol and biomethanol though they are on pilot bases. Biogas (either biomethane or biosyngas) is also a major type of gaseous biofuel mainly produced from anaerobic digestion of POME and/or EFB as well as from the gasification of EFB, OPT, and OPF. Oil palm briquettes, pellets, and other solid biofuels from the solid components of the oil palm biomass also have high potentials in contributing greatly to the world's renewable energy mix.

For a production chain to be sustainable, the production processes as well as the raw materials used in the production must meet the criteria for sustainable development (Chap. 1). The 'value'⁴ of an output resource must be more than that for the input resources for a production process as well as a product to be recognized as sustainable. In order to achieve this many factors must be considered of which most of them are elaborated in the subsequent sections of this chapter.

Prior to the production of biofuels from oil palm biomass, the management practices that are involved in the production or agriculture of the oil palm biomass and subsequent production of palm biofuels become crucial because they largely determine the overall sustainability of the production process as well as the product.

Nonetheless, oil palm biomass production has been under criticism due to its negative impacts on the environment. Again, debatable issues on palm oil biodiesel sustainability are centered on the fact that competition of palm oil for food and fuel may cause an increase in demand for extra palm plantations hence reduction in the tropical rain forest especially in the two leading producing countries of palm oil, Malaysia and Indonesia. In order to deal with these challenges associated with the oil palm production so as to thrive for sustainable development for the oil palm biofuel industry, there has been series of meetings by various stakeholders, farmers, and NGO's under the umbrella of the Roundtable

(Footnote 3 continued)

production. The remaining biomass are dumped at landfills or incinerated without controlled methods of producing energy (Yusoff 2006).

⁴ The 'value' of a resource may lie within its mass, 'energy' or economic contents not leaving out their social and environmental impacts. These indicators may be found by critical assessments of the in-out flows of a production process.

for Sustainable Palm Oil (RSPO) to find possible solutions to ensure sound policy, economic, social, and environmental sustainability for the industry. Principles and criteria set by the (RSPO 2006) for sustainable oil palm production aim at efficient production via best management practices in order to deliver a cost-effective, socially accepted, and environmentally friendly product (mainly palm oil). Organizations like the ‘Reducing Emissions from Deforestation and Forest Degradation’ (REDD+) and the ‘Palm oil, Timber, Carbon Offset’ (POTICO) have also been instrumental entities in the sustainability issues of the oil palm and palm oil productions. These bodies are able to set financial values for the carbon stored in forests as well as giving incentives for reducing greenhouse gas (GHG) emissions from palm oil production (WWF 2011).

On the world oils and fats’ market, palm oil is the most productive and cheapest vegetable oil thus it perfectly meets the criterion of economic sustainability though its economics can further be improved (see Chap. 6). In view of this if a first-generation biodiesel is to be sought for fossil fuel replacement then palm oil biodiesel is undoubtedly at the top.

Process improvement within the palm oil biodiesel production plant may contribute greatly to the overall sustainability of the oil palm biofuel industry. On the other hand, in a system where an alternative fuel is much cheaper, palm oil biodiesel becomes economically non-competitive as is the case today in which fossil fuels are much cheaper than biodiesel and bioethanol. For instance in Malaysia, the government’s subsidies on petroleum diesel as transportation fuel has made it a relatively cheaper fuel compared to biodiesel from palm oil. However, due to the near exhaustion of fossil fuels and its detrimental effects on the environment, they may soon be submerged and renewable energy like palm biofuels may take over in the near future thus the need for sustainable palm biofuel production and consumption.

In this chapter, the production of sustainable oil palm biofuels via best management practices is discussed with main emphasis on best oil palm agricultural practices, sustainable palm oil milling and refining, and finally improved processes in producing various potential types of biofuels from oil palm biomass.

4.2 Palm Oil Production and Sustainable Development

4.2.1 Sustainable Oil Palm Agriculture

According to Conway and Barbier (1990), agricultural sustainability involves the practices which would eventually produce high productivity or efficiency (i.e., high amount of output resources from less input resources) for the benefit of the ecosystem and the people therein. In sum, sustainable agriculture:

- Conserves soil fertility, landscape, and biodiversity.
- Ensures the continuous supply of healthy and cost-effective products following the generally accepted principles of sustainability for the benefit of mankind.
- Ensures the use of minimal amount of renewable resources (materials and energy) to produce maximal amount of product according to the standards for sustainable development.
- Ensures efficiency in field management practices.
- Produce less wastes or pollutants.

Sustainable oil palm agriculture involves the use of production practices which adhere to the principles and criteria set by the round table on sustainable palm oil (RSPO) which eventually benefit the entire ecosystem. In 2010, the RSPO introduced a new method called the new plantation procedure (NPP) which in fact is not an addition to RSPO principles and criteria but rather a reinforcement of the existing ones. The seven major steps involved in the NPP which adhere to principle 7 of the RSPO guidelines are:

1. Social and environmental impact assessments of new areas to be developed into oil palm plantation.
2. Interested bodies or companies present their impact assessment results to RSPO for further management plans before new planting.
3. RSPO certification body verifies the plausibility of the impact assessment results and management plans.
4. Companies notifies the public about their impact assessment results.
5. 30-day period is given to the public to submit any complaint against the new oil palm plantation.
6. Companies then resolve any grievances that arise during the 30-day public submission.
7. Upon approval by RSPO and the public, the company then begins the new oil palm plantation.

The RSPO principles and criteria for sustainable oil palm production (RSPO, 2007) are outlined in Table 1.1 (Chap. 1) and summarized below:

- Improved efficiency in nutrient applications by 50 % (criteria 4.2, 5.3)
- There should be no prophylactic use of pesticides and herbicides (criteria 4.5, 4.6)
- Environmental impact assessment must be carried out periodically for plantation systems of more than 50 ha (criteria 5.1, 5.2, 7.1)
- The use of non-renewable fuels like petroleum diesel for production must be reduced by 50 % (criteria 5.4, 5.6)
- Periodic assessment of social impacts for all processes and developments must be carried out for system more than 50 ha (criteria 6.1, 7.1)
- Small holders must recycle their EFB and POME as nutrients (criteria 6.10)
- About 75 % of every new plantings must be cultivated on degraded or abandoned and deforested land rather than forests (criteria 7.3)

- All palm oil mills must treat POME in order to ensure zero discharge (criteria 4.4, 5.3)
- Palm oil mills must increase their oil extraction ratios to at least 22 % (criteria 3.1)

Apart from the principles and criteria set by the RSPO for sustainable palm oil production, Table 4.1 also summarizes some important ways or recommendations for achieving sustainability during oil palm cultivation.

For oil palm nurseries to adhere to sustainability principles, the use of forest soils which could result in biodiversity loss must be avoided. Instead, wastes from

Table 4.1 Best management practices for sustainable oil palm cultivation

Agricultural practice	Implementation method
1. Soil protection	Reduce soil erosion and leaching by growing cover crops
2. Pests, weeds and diseases control measures	Increase diversity of oil palm species or varieties in order to avoid the spread of diseases and pests from one crop to another hence reduction in chemical pesticides etc. Pesticides and weedicides with reduced environmental effects must be used Rodents could be eliminated by in-crop monitoring systems like traps Encourage mosses, soft grasses, and ferns to grow under older palm trees in place of competitive weeds
3. Nutrients recycling and fertilization	Use of nitrogenous crops such as legumes for intercropping to add nutrients to the soil Pruning and harvesting residues such as OPL, OPF etc. must be recycled for soil fertilization Organic fertilizers like animal dung could be used in place of chemical ones to supplement the soil nutrition There must be regular analysis of the soil to ensure good nutrition for the oil palm tree
4. Energy efficiency methods	Reduce the use of fossil fuel in tractors and other equipment during irrigation and clearing of land for plantation by using solar driven machines and equipment or mechanized weeding systems. ^a Replace high energy consumption machinery with more efficient ones Energy efficiency assessment must be done regularly to improve the farming practices
5. Pollution and wastes minimization	Harvested residues could be used as feed for the incorporated animal husbandry in the farm Wastes could be recycled or utilized for value-added bio-products Minimize pesticides and fossil fuel use
6. Forest and biodiversity conservation	Bush burning which drives away wildlife must be replaced with mechanized weeding

^a Animal husbandry can be incorporated into the oil palm plantation whereby the animals could graze the weeds, clear the land during replanting or harvesting etc. in order to reduce the dependency on bush burning, fossil fuel use etc.

the mills such as EFB, POME etc. must be composted, mixed with topsoils from disease-free areas, and used for nursing the new oil palm plants without clearing forests. Water is a major resource used during nursery, plantation, and oil milling and efficient use of water in agriculture is a determining factor for sustainable development (Rockström et al. 2010). During seasons where rain water is not sufficient for new oil palm plants especially the nursery, irrigation is resorted to. One way of utilizing rain water sustainably in the nursery and the plantation is to establish rain water harvesting systems for storage and subsequently using it for irrigation during nonrainy seasons. Efficient irrigation systems like drip systems unlike sprinklers must be used for watering nurseries. Sprinklers are found to waste much water during irrigation as water from the sprinkler may fall on non-focused watering areas. Alternative sustainable irrigation methods in the plantation involve the construction and use of in-field dams and water catchment systems. Wastewater from the oil mill or other sources can also be treated to an acceptable biological oxygen demand (BOD) and chemical oxygen demand (COD) contents before using for irrigation. Buffer strips must be placed around drainages or run-offs from irrigation in order to prevent chemicals from the soil from entering directly into water-bodies. Principles and planning methods for efficiency in water utilization must be encouraged to help monitor the use of water as well as the elimination of wastes from the plantation.

Presently, in almost all the palm oil mills in Malaysia and Indonesia, EFB, PPF, PKS etc. that are generated as wastes are normally under-utilized on commercial scales. Meanwhile, they could have been used as mulching materials as well as nutrient supplements to the oil palm trees when efficiently applied in the plantation. Kala et al. (2009) have reported the efficacy of using EFB together with other oil palm solid residues like OPF, OPL, and OPR as mulch and fertilizer with better properties and growth performance compared to the inorganic fertilizers that are environmentally unsafe.

The growing of cover crops for nutrients addition to the soil is found to be cost effective compared to compost or other organic fertilizer (Conway and Barbier 1990) prepared outside the oil palm industry. However, the integration of animal rearing into the oil palm plantation may reduce the cost of fertilizers and fossil fuel for weeds clearing. During cultivation, the animals' dung could be used as manure while the animals also graze the weeds and herbs in the plantation with or without cover crops. Again, the avoidance of heavy tracks and machinery which may leave shallow pot holes and gutters in the plantation during rainy seasons must be encouraged so as to prevent erosion from occurring. Other measures to prevent soil erosion within the plantation include the establishments of soil erosion terraces, silt pits, and water diversion channels along potential places of soil erosion occurrences. In most cases where there exist severe sloppy lands, terracing may not be economically viable hence plantations must not be established on lands with severe slopes. Again, conservation tillage as well as crop rotation programmes must be usual practices in oil palm cultivation in order to minimize erosion and run-offs.

One major challenge facing the efficient production of FFB is the presence of mammalian pests which include squirrels, rats etc. which damage new plants and fresh fruits. Their presence in the field is actually inevitable thus for efficiency in cultivation, owl nest boxes or traps must be placed at vantage points to control their activities. Epiphytes growing on the OPT must be left unremoved in order for them to provide a habitat for potential predators that usually feed on the major pests. In order for sustainable oil palm cultivation to be a reality, weeds and herbs resistance must be controlled by carefully planning the ways and durations for weedicides and herbicides use.

On the issue of biodiversity loss during land preparation for oil palm plantation, there must be strict programmes which would see to the intensive assessment of environmental impacts for the suggested area. Bush burning as a practice for land clearing for oil palm cultivation is found not to only contribute largely to deforestation especially in Malaysia and Indonesia but also cause fire outbreak in nearby farms and forests which eventually endanger the lives of animal species (Glastra et al. 2002). New plantations which would remove primary forests must be avoided so as to curb these menace.

Peat land management plays an important role in the sustainable development of oil palm cultivation. Peat consists of heterogeneous plant materials that have decomposed and accumulated in water-saturated environment while peat land is the area occupied by the peat. Because peat lands are able to store carbonaceous materials, they are found to play vital role in maintaining a balance in the atmospheric carbon cycle by mitigating against climate change. In this regard, peat lands must be protected and managed well to save the environment. Oil palm growers in Indonesia and Malaysia have resorted to peat lands because of their unique properties like richness in organic fertilizer that are beneficial for oil palm agriculture especially when they are maintained at appropriate water-table. About 25 and 12 % of oil palm plantations are on peat lands in Indonesia and Malaysia, respectively (Silvius 2006; Wahid 2009). The recommended sustainable practices for peat land management in oil palm agriculture include:

- Ensuring optimal ground water-table at 30–50 cm to increase nutrient efficiency, minimize peat oxidation, and ensure irreversible peat drying which eventually reduce CO₂ emissions (MPOB 2011).
- Compaction of the peat to improve the oil palm growth and yield.
- Regular maintenance of water systems must be carried out to conserve suitable ground cover and minimize erosion.

Environmental degradation resulting from fossil fuel combustion during clearing of peat lands and rain forests for oil palm plantation has again contributed tremendously to rise in climate change in Indonesia and Malaysia. As a result, since the late 1990s, the oil palm industries in these countries have been involved in sustainable farming practices which has helped the industry to minimize biodiversity loss and increase economic value of the oil palm. In Malaysia for instance, out of the total agricultural land area of about 6.27 million hectares,

about 4.18 million hectares ($\sim 67\%$) is occupied by oil palm plantation (OECD-FAO 2011) though yearly increment is observed with insignificant hectares of forest land. Majority of expanded plantation areas, however, have been the converted areas of rubber, cocoa, and coconut farms that are no more in operation. Meanwhile, about 65 % of the total land area in Malaysia is currently covered with forest which is contrary to the situations in many other developing countries where more than 70 % of their land areas are used for agriculture (FAO 2005; OECD-FAO 2011). Nonetheless, the palm oil industry aims for sustainable development as it is set to face a major challenge with the conservation of forest and wildlife as the world's population keep growing with high growing demand for oils for food and fuel. As a way to combat this problem, Malaysia has come up with a policy concerning the clearing of new forests for agriculture.

The carbon credit projects through the clean development mechanisms (CDM) has been investing in new oil palm plantation for biofuel production in a more sustainable way. Small scale palm oil producers have been the main contributors to sustainable oil palm production in the world both in Africa and Asia. In 2010 for instance, small scale producers of palm oil in Malaysia, Indonesia, and Papua New Guinea were certified by the RSPO as certified sustainable palm oil (CSPO) producers (MPOB 2012). In 2011, the smallholders in Malaysia and Indonesia contributed about 52 and 38 % of the total CSPO produced, respectively, (MPOB 2012). In 2012, RSPO recorded a total of about 6.6 million tonnes of CSPO from about 1.2 hectares of land at a growth rate of about 20 % (MPOB 2012) with Indonesia as the largest CSPO producer (overtook Malaysia in 2011) certified by the RSPO. Again, Patum Vegetable Oil Company Limited⁵ in Thailand has also been certified by the RSPO as CSPO producer in 2012.

Another RPO producer in Papua New Guinea called New Britain Palm Oil Limited (NBPOL) and formerly the fifth largest producer of CSPO in both production capacity and plantation area is also now certified as the third largest CSPO producer worldwide with the help from their smallholders. However, lack of capacity building, unavailability of funding opportunities, and other constraints in African countries especially Ghana, Gabon, and Liberia, have prevented many smallholders of oil palm plantations to adhere to sustainability principles in order to be recognized as CSPO producers. The benefits of embracing sustainability with great efforts are worthwhile compared to the lasting impacts incurred during poor production. This implies that responsible agricultural practices are not only beneficial for the environment but also commercially advantageous to the economy of a nation as cost-effective products are finally produced.

In order to achieve the social or responsible employee consideration principles set by the RSPO for sustainable oil palm cultivation, employers must adhere to legislation on employment benefits and working conditions. Good relationships

⁵ Patum Vegetable Oil Company Limited (a biodiesel producer) is the largest exporter of refined palm oil (RPO) in Thailand and every month, this company contributes about 80 % of the total RPO exported in Thailand (RSPO).

between workers and managers of the industry as well as nearby community and the nation as a whole must be encouraged and maintained. Employers must ensure regular human capital development for their workers and access to incentives in the form of housing, medicals, education, and recreational facilities to workers and their families.

In sum, oil palm agriculture must aim at cost-effective products (i.e., the FFB) thus the need for good agricultural practices to ensure high product yield and quality. During pruning, harvesting, loading, and off-loading of the FFB, care must be taken in order not to inflict bruises on the fruits which may eventually increase the FFA content of the oil and decrease the quality of the oil. Good harvesting practices leading to high harvesting efficiency may help increase the value (quality and quantity) of FFB produced. Other contributing factors to the final composition and quality of the palm oil are the oil palm variety used for the propagation, the tree's age, cultivation management methods, transportation methods etc. which need to be controlled in order to achieve sustainability.

Pollution control has been one other major challenge facing the RSPO as there are no outlined standards to measure and minimize the emissions of GHGs from the plantation, the oil mills, and the palm biofuel production plants. The major contributions of GHGs from the oil palm industry result from the clearing of land for new plantations which involve bush burning, deforestation, fossil fuel combustion etc. Though there exist sustainable practices which are currently being implemented by some the certified members of the RSPO for sustainable oil palm and palm oil production, these technologies (like methane and CO₂ capture) are not economically viable to small holders hence the RSPO are still working hard to come out with standards which clearly spell out major sustainable principles of ensuring minimal emissions from the oil palm industry.

Again, the goal of the RSPO to alleviate poverty as part of maintaining sustainable oil palm production for small holders is in fact difficult to achieve as most of these smallholders have to replace their existing trees with high-yield oil palm varieties. For the period when they would be waiting for harvest, they would probably be rendered jobless. Incentives from government and nongovernmental agencies could help solve this menace. Best management practices for the oil palm and palm biofuel industries can easily be realized for sustainable development when there are implemented policies mandating subsidies and incentives on palm biofuels production.

4.2.2 Palm Oil Milling and Sustainable Development

In the palm oil mill, two main types of oils namely CPO and CPKO are normally produced from the FFB that are processed. These oils are produced by separate units which basically comprise similar equipment. According to RSPO, sustainable palm oil production comprises legal, economically viable, environmentally appropriate and socially beneficial management, and operations for the benefit of

the people. FFB which are produced in a sustainable manner add more value to the products like CPO and CPKO produced during the milling processes.

Commercial palm oil mills normally process about 3–60 tonnes of FFB per hour (with extraction efficiency of 20–25 % CPO per FFB) and may operate in batches or continuously depending on the availability of the FFB (Poku 1993; Yusof 2007). The energy used to drive the machineries in the mill are mostly sourced from the solid residues like EFB, PKS, PPF etc. that are generated by the mills and regarded as wastes. Almost all the palm oil mills in Malaysia and Indonesia use the mechanical or physical milling processes which do not involve the use of chemicals. Harvested FFB should be taken to the palm oil mill as soon as possible (normally within 48 h after harvest) to maintain the quality⁶ of the palm oil after milling. In cases of delay, the FFB may over-ripe where the exocarp is softened and easily exposed to lipolytic enzymes which may result in increase in FFA content in the oil which may need additional energy to remove them during palm biofuels production. In view of this, for a sustainable palm oil milling, the oil mill must be sited very close to the plantation to facilitate rapid transportation and on-time processing of the FFB.

Immediately the FFB are brought into the mill, they are put into boxes for checking and subsequent weighing while in large-scale or commercial production, they are weighed directly in the tracks that conveyed the FFB into the mills. The FFB are then sterilized with saturated steam at 3 bar and 140–150 °C for 1–1.5 h (Yusof 2007) in order to inactivate the processes of enzymatic splitting of oils, hydrolysis, and auto-oxidation which give rise to high FFA in the CPO. In a rotating drum thresher, the sterilized FFB are stripped to separate the fruitlets from the EFB.

In a mechanized system, the fruitlets are separated from the nuts by continuous stirring, then digested into mash with steam after which they are further screw-pressed to release the mesocarp oil. For smallholders, the separation of the fruitlets from the bunches are done manually while the sterilization is also done by cooking in hot water (using EFB as fuel) due to the absence of facilities for commercial steam production. During digestion, the fruitlets are mashed by direct injection with steam during which the oil-bearing cells of the fruits get ruptured exposing the fragile mesocarp for efficient oil pressing. The digester consists of a vessel or tank with stirrers fitted on rotating shafts which are able to pound the mesocarp fiber to release the oil after pressing.

In order to increase the viscosity of the CPO, elevated temperatures are normally used during digestion of the palm fiber mash which is not an encouraging practice for sustainability in terms of economic and environmental considerations. The palm kernel nuts (PKN) are then sent to the PKO extraction unit while the PPF are dried for use as fuel in the boilers. The pressed oil which contains about 35–45 % CPO and 45–55 % water is clarified in tanks (at 80–90 °C in order to facilitate oil separation) to remove all dirt and foreign materials prior to high-speed

⁶ FFB plucked from the palm tree are immediately subjected to oxidation which leads to rapid rise in free fatty acid (>0.3) content of the oil (which is not economical when used raw material for biofuel production). In order to avoid this reaction to affect the oil, the FFB must be processed immediately to maintain its quality.

centrifugation and vacuum drying (Yusof 2007). The clarifier sediments are further purified to recover additional oil and the leftover sludge called the palm oil mill effluent (POME) which is discharged into the effluent treatment unit for further treatment. The dried CPO is then stored for further refining or sold without refining.

In some palm oil mills, the palm kernels are not processed into PKO but are stored for other purposes like solid biofuels for black and goldsmiths or dumped in landfills. In the PKO extraction unit, the nuts recovered after digestion and mashing of the fruitlets (in the CPO extraction unit) are cracked in centrifugal crackers to separate the PKS from the kernels with the help of a clay bath or winnower. This is done after drying the nuts. During the nut cracking process some of the kernels are broken. The rate of FFA increase is much faster in broken kernels than in whole kernels. Breakage of kernels should, therefore, be kept as low as possible by using efficient equipment. The kernels are then pretreated to remove unwanted materials like stones, metal debris, particles of PKS etc. using vibrating screens or magnetic separators before flaking, cooking, and screw pressing to extract the palm kernel oil.

During the pretreatment stage of PKO extraction, the cleaned kernels are ground into smaller pieces with the help of hammer grinder before flaking in the roller mill. The flaked kernels are then steam conditioned or cooked in order to break open the cell walls of the flaked kernels for effective oil release. Cooking is also done to adjust the moisture content of the flaked kernels and reduce the viscosity of the oil which would be extracted. The efficiency of the pretreatment stage would eventually determine the yield and quality of the CPKO produced. After pretreatment, the cooked kernels are fed into the screw press to extract the CPKO which is then clarified to remove solid impurities with the aid of filter press. The PKC discharged from the screw presses as co-products are stored for other purposes like feed and biofuel feedstocks. The basic stages involved in the production of CPO and PKO are summarized in Fig. 4.1. All the waste steams from the plant can be utilized for biofertilizers, biofuels, or other value-added bio-products which could enhance the sustainability of the production plant (see Appendix G).

For a sustainable CPO and CPKO production, Fig. 4.2 outlines basic strategies which serve as stepping stones in adhering to the principles of RSPO for sustainable palm oil production.

4.2.2.1 Processes of CPO and CPKO Refining and Sustainable Development

In Malaysia, out of the over 428 existing palm oil mills in operation, only about 57 have refinery units for the processing of the CPO and PKO into their refined, bleached, and deodorized forms. Oil refining removes undesirable components like gums, FFA, water, pigments, odouriferous substances, and other impurities in order for the oil to meet the food, oleochemicals, and biofuels industries' standards.

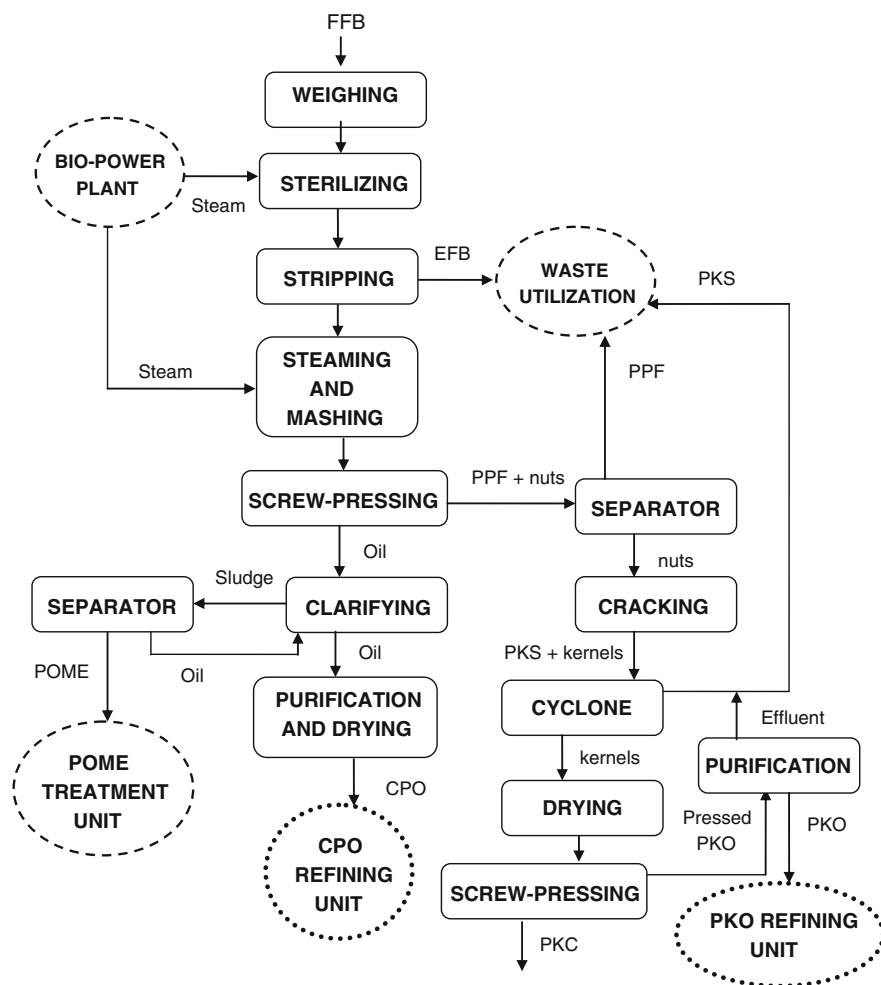


Fig. 4.1 Schematic diagram for CPO and PKO extraction processes

CPO and CPKO are mostly refined by two major processes namely physical (or steam) and chemical refining. More than 90 % of palm oil mills in the world use the physical method of refining CPO and CPKO because it requires less input resources, it is cheaper, simple, and gives high oil yield.

Physical refining processes involve degumming, bleaching, deacidification, and deodorization of the CPO and CPKO. Gums and FFA in CPO and CPKO are the major concerns for oil palm biodiesel producers since these impurities tend to contaminate the biodiesel which demands further energy for removal. Degumming is the process in which the impurities like phospholipids, gums, proteins etc. that are insoluble in the oil during hydration, are removed. The commonly used degumming methods include alkaline, hot water, and enzymatic degumming.

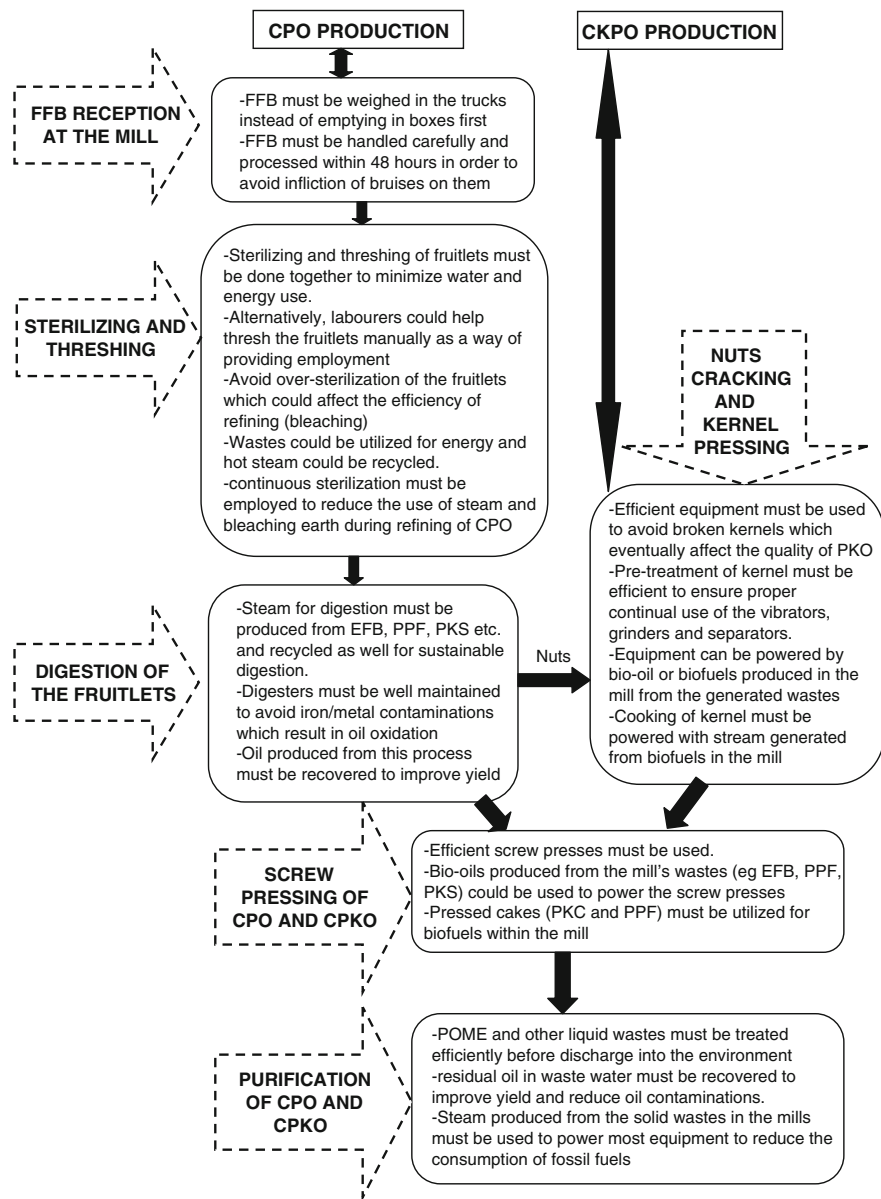


Fig. 4.2 Strategies for ensuring sustainable CPO and CKPO production

In physical degumming process, hot water is added to the oil in a hydration tank where the gums are allowed to agglomerate after which the mixture is separated into oil and gums by a separator. The degummed oil then enters the bleaching unit prior to vacuum drying while the gums are stored for other purposes. Bleaching is

done to remove coloring components like carotenoids from the oil in order to enhance the oxidative stability of the oil for efficient biodiesel production.

In the bleaching tank, the degummed oil is mixed with bleaching earth (also called fuller's earth or natural clay) at temperatures of 90–130 °C and at low pressure to precipitate the phosphatides, pigments, bacteria, and other trace metals or impurities in the oil (Ceriani and Meirelles 2006). Natural clay has adsorptive properties which are able to chemically attract the impurities from the oil onto itself during bleaching and the oil is recovered by filtration (Cheah and Siew 1999). In some instances, activated carbon which has similar adsorptive properties with those of natural clay is also used for bleaching because of its high yield capabilities. However, due to its high cost and high oil retention, natural clay or acidic clay is mostly preferred. The utilization of activated carbon from EFB, PKS, PPF etc. by an independent plant nearby the mill may reduce the cost of refining CPO and CPKO hence adding more value to the oil palm industry in terms of sustainable economic and environmental production. After clay bleaching, the used clay can be recovered and treated for further use. However, in almost all the CPO and CPKO refineries, this practice is not done but the used clay is discharged together with the waste liquids from the bleaching process causing environmental problems.

Deodorization of oil is a process of removing volatile and odouriferous materials in the oil by high vacuum steam distillation at high temperature between 180 and 270 °C (Cheah and Siew 1999). During this stage, the FFA (which is reduced to about 0.05 %), aldehydes, ketones, and other remaining volatile compounds are stripped off in a column. The refined oil obtained at this stage contains triglycerides of various components that are easily separated by dry, solvent, or detergent fractionation methods. After fractionation and filtration of the bleached CPO and CPKO, palm olein (liquid fraction) and palm stearin (solid fraction) are obtained. The deodorized oil is then cooled and stored while the palm fatty acid distillates (PFAD) is recovered and stored as well. For the production of food-grade palm oil, the deodorized palm oil is further fractionated into liquid form (palm olein which is commonly used as cooking oil) and solid form (palm stearin). After the complete stages of physical refining of CPO and CPKO, the major products recovered are refined, bleached and deodorised palm oil (RBDPO), palm stearin, palm olein; and refined, bleached, and deodorised palm kernel oil (RBDPK), palm kernel stearin, palm kernel olein, respectively. Figure 4.3 summarizes the production processes of CPO and CPKO refining into PFAD, palm stearin, and palm olein.

During chemical refining of CPO and CPKO, the oil is first degummed through the same process as described above for physical refining degumming except that alkaline is used instead of hot water. The oil is mixed with aqueous alkali mostly sodium hydroxide or sodium carbonate at 75–95 °C (Franke et al. 2009) where the FFA in the oil react with the alkali to form soap which is subsequently washed and separated by centrifugation. After this process, the non-hydratable gums (about 0.3–0.6 %) are further removed by the addition of phosphoric or citric acid (neutralization) followed by water washing. The solid phase containing the phosphatides, soap, water, and some amount of oil can be recovered individually

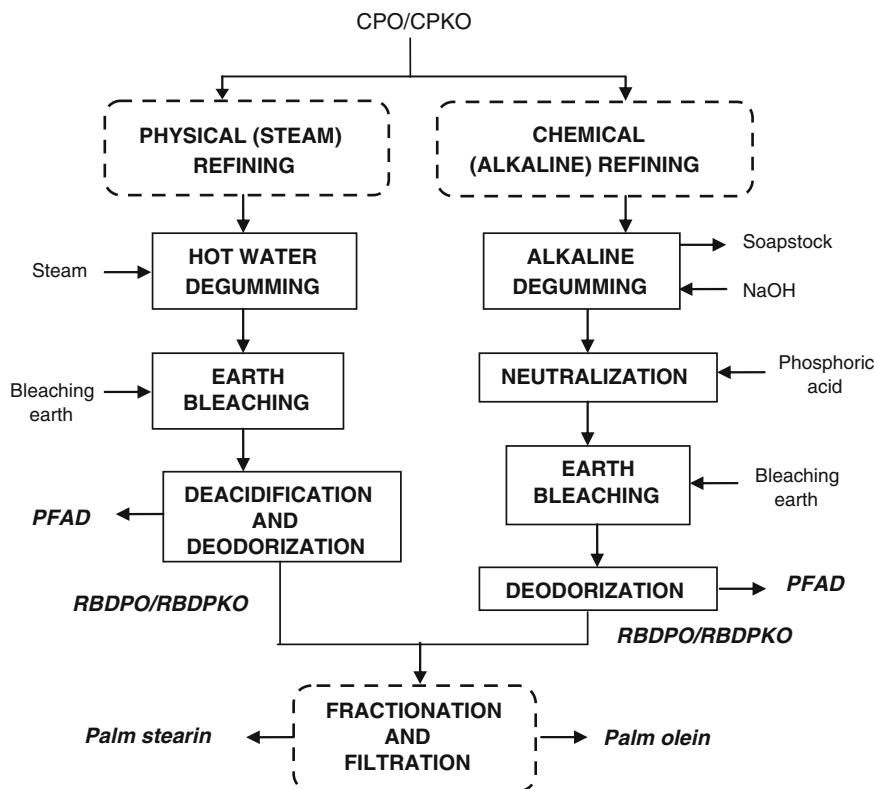


Fig. 4.3 Schematic flow diagram for physical and chemical refining of CPO and CPKO into various palm oil components

through appropriate methods to ensure sustainable utilization of the wastes. After drying the neutralized oil, it is then bleached by adsorption following the same procedure as described for clay bleaching process above. The bleached oil is then deodorized followed by fractionation into palm olein and stearin with PFAD being the main distillate. Due to environmental pollution as well as economic constraints of using chemical refining methods, most palm mills are resorted to the physical refining of CPO and CPKO. Table 4.2 outlines some practical methods of achieving sustainable production of RBDPO and RBDPKO prior to biodiesel production.

Recent researches (Cowan et al. 2008; Yang et al. 2006; Jiang et al. 2011; Ciofalo et al. 2006) have reported the successful use of enzymes for sustainable CPO and CPKO refining. Enzymatic refining is also found to reduce the FFA in the oil by 40–60 % (Cowan et al. 2008). During enzymatic degumming, the enzymes eliminate the emulsification properties of the oil which eventually produces quality and high oil yield (i.e., 96–98 %). The life cycle assessment (LCA) of enzymatic method of refining oils and fats have been found to reduce the negative

Table 4.2 Sustainable RBDPO and RBDPKO production practices

Key area	Sustainable production practices
Environment	Less generation of wastes such as wash water, heat/steam emissions. Reduce the use of fossil-based fuels for heat, electricity, and steam production. EFB, PPF, PKS from the mill can be used to produce biofuels for use in the refining unit Condensation and recycling of process steam and water. Scrubbers can be used to remove air pollutants before discharging into the environment Recycle spent bleach PFAD, palm olein, palm stearin, soap stocks, removed pigments, and gums can be converted into value added bio-products.
Energy use	Audit existing systems to find out where energy use can be improved Hot oils or water can be used to heat feeds Evaporated water can be condensed for reuse
Economic	Process efficiency must be ensured to improve the quality and yield of the product (oil) Reduction in the consumption of ‘energy’ leads to cost-effective process To improve the oil yield, the residual oil mixed with the effluent from each processing stage can be recovered by the help of de-watering and decanting centrifuges
Social	Safety measures should be adhered to by workers in the production plant
Policy	Subsidies and incentives from governments can be given to smallholders of palm oil refineries who are able to process their CPO and CPKO into their refined forms in a more sustainable way.

environmental impacts created by the chemical method of refining (Cowan et al. 2008). For instance, enzymatic degumming of soybean oil is found to save energy, reduce GHG emissions, acidification, and smog formation compared to the chemical and physical (hot water) degumming methods. One major problem with physical and chemical degumming methods is the emulsification of the gums with the oil which eventually reduces the oil yield and quality. Again, the cost of enzymes have been a major challenge to the sustainable production of RBDPO and RBDPKO. Process development or improvement as well as sustainable production technologies could help minimize these cons. Figure 4.4 shows the energy consumption as well as the environmental impacts of enzymatic degumming compared to the other methods.

4.3 Sustainable Production and Consumption of Palm Biofuels in Palm Oil Mills

The main aspects of waste management as key principles to sustainable development include recycle, energy recovery, and waste utilization or reuse. Applying these principles to oil palm biofuels production and consumption in a single system

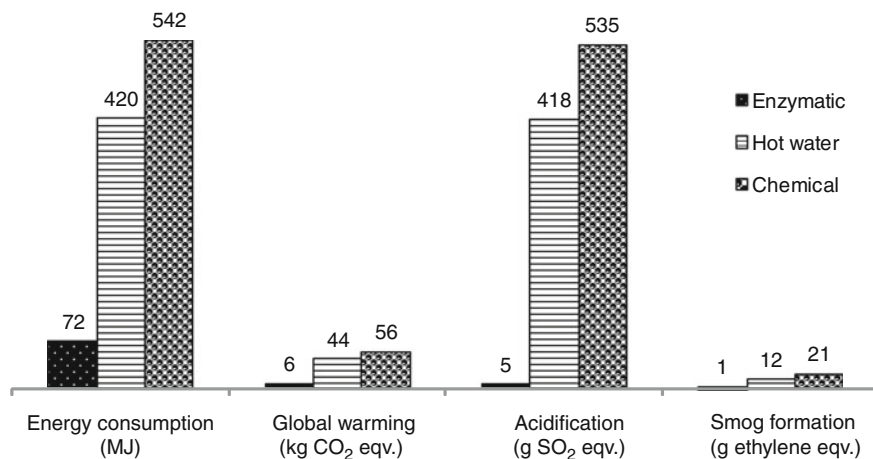


Fig. 4.4 Environmental impacts of different degumming methods used by palm oil mills

would help sustain both the oil palm and palm biofuels industries. About 24.7 TWh bioelectricity can be generated from palm wastes generated annually by the oil palm industry (MOPS 2002). Though only about 0.972–1.5 TWh of this generation capacity is used by the palm oil mills, the rest can be directed to the national grid which can be used to serve about 10 million people in the world (MOPS 2002).

In the palm oil mill, second-generation gaseous palm biofuels like biosyngas, biomethane, and biohydrogen are potential biofuels that can be produced. POME, which results from FFB sterilization and clarification of the CPO is mostly utilized for biogas production which is used to supplement the boiler fuel via combustion in biogas engine generator. Biogas production from multi-feedstocks like POME and EFB have been reported by O-Thong et al. (2012) to enhance microbial biodegradability and increase biomethane yield compared to the single feedstock utilization. The slurry obtained after anaerobic fermentation of POME for biomethane recovery can be directly used as biofertilizer in the oil palm plantation hence saving inorganic fertilizer cost (Ngan 1999).

EFB, PPF, and PKS are the commonly used oil palm biomass for the production of heat (bioheat) for biosteam and bioelectricity generation and these bioenergy sources are directly consumed within the palm oil mills. Currently, only gaseous palm biofuels are generated in the palm mills though the production of solid palm biofuels like briquettes, pellets, and torrefied biomass could be integrated into the palm oil milling system for sustainable production. Excess bioelectricity generated from the palm mills could be sold to the national grid.

In the palm oil mill, the processing of a bunch of FFB (weighing about 15–25 kg) results in the generation of about 4.8 kg of CPO, about 1 kg CPKO and

nearly 13–14 kg of residues⁷ in the form of EFB, PPF, PKS, and POME (Yusof 2007). Presently, in the large and medium scale palm oil milling plants, these wastes are normally utilized as bioler biofuels for steam production within the oil mill as a way to meet the criteria for sustainable production. Generally, PPF and PKS form large composition of palm wastes used in the medium and commercial scales palm oil mills to generate superheated steam for bioelectricity production and other purposes. Bioler ash is mostly recycled for use in the plantation as biofertilizer but the large portion is dumped at landfills. With smallholders, these wastes are either returned into the plantation for mulching and nutrient recycling or dumped without proper utilization hence resulting in environmental hazards. Only a small percentage of the solid residues generated by the smallholders are burnt for heating purposes during sterilization of the FFB. This method of utilizing the wastes is not environmentally sustainable due to the emission of smoke and other pollutants upon direct and incomplete combustion of these biomass.

4.3.1 Current Technologies for Sustainable Production of Second-Generation Palm Biofuels

Presently, the common types of technologies employed for palm biofuels and bioenergy production within the palm oil mills are combined heat and power (CHP) generation commonly called cogeneration and anaerobic digestion (or fermentation). Most large and medium scale palm oil mills in Malaysia and Indonesia are involved in one or both of these technologies for sustainable production of bioelectricity and steam to run the palm oil mills.

Pyrolysis and gasification of EFB, PPF, and PKS have not be explored for palm biofuel production by the palm oil mills in Malaysia and Indonesia though they are also potential technologies for palm biofuels production. Because most of the EFB, PPF, and PKS are still left after biomass cogeneration, for the sake of sustainable development for the industry, there should be funding opportunities (which could be in the form of loans), incentives, and subsidies available as supports from governments to palm oil millers to tap the technologies of pyrolysis and gasification for biohydrogen and biosyngas generation to serve nearby communities. Wastes utilization in this direction would help reduce the cost of biofuels eventually. Thus the crucial need to improve the technologies for high yields and effectively disseminate the advantages of resorting to biofuels produced in a more sustainable way to the general public.

⁷ Out of the wastes produced in the oil mill, EFB, PKS, PPF and POME form about 3.22–3.50, 0.84–0.98, 1.96–2.11 and 6.50–7.42 kg respectively (Yusoff 2006).

4.3.1.1 Oil Palm Biomass Cogeneration Systems for Steam and Bioelectricity Production

Cogeneration is the sequential or simultaneous production of various forms of useful energy (mostly heat and power) from a single primary energy source. Cogeneration systems which utilize biomass as feedstock has many advantages over the conventional CHP which make use of fossil fuels. Biomass cogeneration systems can save up to about 40 % of the primary energy with overall energy use efficiency not less than 80 % compared with the conventional fossil fuel fired power plants (Husain et al. 2003; Bahadori and Vuthaluru 2010). Again, biomass cogeneration help reduces the GHGs emissions for every useful energy produced compared to the conventional ones. Large and medium scale palm oil mills have onsite biomass cogeneration plant which is advantageous considering transmission line losses and impacts on utility networks in getting electricity from national grid. In most palm oil mills in Malaysia and Indonesia for instance, the cogeneration systems utilize mostly PPF and small amount of PKS to generate steam for FFB processing. The economic and environmental sustainability of the palm oil milling processes are almost achieved when the solid residues from the mills are utilized as feedstocks for cogeneration.

A typical cogeneration system used by many palm oil mills consists of heat engine, generator, heat recovery boilers, and electrical networks which have been integrated in one system. The types of heat engines for cogeneration include gas turbines, extraction or back pressure steam turbines, and reciprocating engines. Figure 4.5 shows the efficiencies of the main types of heat engines used for power and heat production.

A back pressure or condenser vacuum steam turbine installed with water-tube boiler system presents the simplest, highly efficient (about 92 %), and cost-

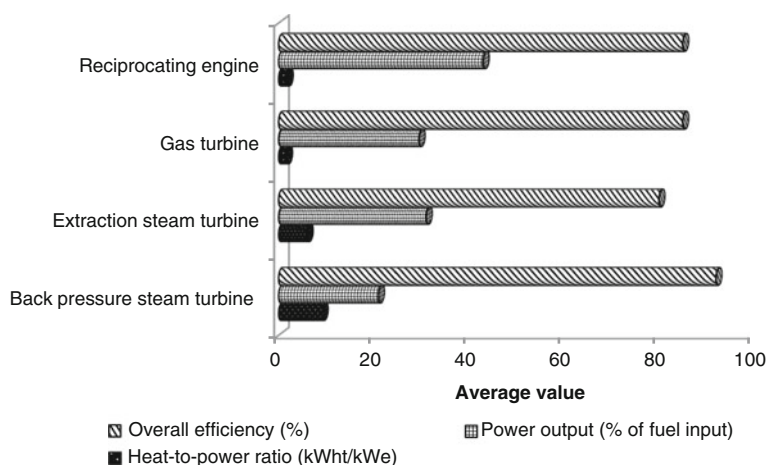


Fig. 4.5 Performance efficiencies of the types of heat engines for biomass cogeneration

effective configuration commonly used by many mills (Bahadori and Vuthaluru 2010). PPF, PKS, or EFB is fired in the heat engines to generate mechanical energy which is then used to drive the generator to produce electricity. Heat energy from the system is used for either direct processing or indirect generation of steam and hot water for processing FFB. Steam that is generated at, approximately, 23 bar from the boiler is passed through the back pressure turbine to generate electricity which is used by the mill. For maximum energy and equipment efficiencies, the steam temperature and pressure at the entry feed into the steam turbine must not vary widely with the optimum conditions of the turbine. Boiler fouling as well as process control errors which could lead to variations in steam conditions must be avoided. System and units maintenance must be routinely carried out to improve the efficiency of the cogeneration system. During hot weather conditions, it would be necessary to cool the inlet air.

For sustainable bioenergy production in the palm oil mill, high efficiency heat engine must be chosen. Most palm oil mills have over 90 % cogeneration efficiency with small amount of biomass entering the boiler as feed. In cases where most of the oil palm wastes are fed into the cogeneration system, all the generated bioenergy is not utilized in the mill. For instance, PPF generated from the processing of 1 tonne of FFB could produce about 40–42 kWh bioelectricity and about 350 kWh heat in which only about 15–17 kWh bioelectricity is needed by the plant for 1 tonne FFB processing (Chan et al. 2002). When all the EFB, PPF, and PKS produced from the processing of a tonne of FFB are used to feed the cogeneration system, about 132 kW bioelectricity could be produced. Thus for an average palm oil mill with a capacity of about 60 tonne/hr FFB, about 2520 kW bioelectricity is produced with the mill utilizing only about 1020 kW bioelectricity for sterilizing, clarification, digestion, and drying (Chan et al. 2002). The remaining could be sold by nearby companies or connected to the national grid in order to add more economic value to the oil palm industry. Whenever the palm oil mill is not running, petroleum diesel is used to produce electricity with the help of a diesel generator. CPO, RPO, and PFAD have been reported to have good fuel properties to be used in diesel engines (Choo et al. 2002) hence could be used in place of fossil-based diesel for bioelectricity production in the oil mills.

Sustainable production of heat and power from EFB, PPF, and PKS in the mill can be realized when the cogeneration system is improved for efficient operation. Air preheaters and economizers that are incorporated into the cogeneration system is found to improve the overall boiler efficiency (Chan et al. 2002). Due to variations in moisture contents of the wastes used to feed the boiler for cogeneration, a shredder, and dryer can be used (most palm oil mills do not have shredders) to reduce the material sizes and moisture content to at least 40 % before firing which would improve the combustion process. The combustion equipment could also be improved in order to process different kinds of biomass at the same time. The cogeneration system must be automated for feed entry, combustion control, and boiler ash removal in order to maintain efficient production of energy as well as waste removal with less emissions. Gas scrubbers must be installed in various chimneys to trap black smoke emissions that could harm the environment.

4.3.1.2 Anaerobic Digestion of POME and EFB into Biomethane-Rich Biogas

Liquid effluents (i.e., POME) from various unit operations of the palm oil mill are generated in large amounts by the medium and large-scale palm oil mills. Formerly, almost all the palm oil mills were discharging their POME into nearby rivers without proper prior treatment thus causing water pollution. Smallholders of palm oil milling who operate closer to the plantation easily discharged their untreated POME into nearby bushes. Though they may be in small amounts, their long-term impacts on the environment are detrimental. In medium scale mills, POME is discharged into nearby gutters or pits purposely dug for such purposes. These discharge sites may emit odouriferous chemicals and gases which are harmful to the neighborhood and the entire environment. Ashes and charcoal resulting from biomass combustion for heat generation during FFB processing are normally used by smallholders to adsorb some of these odors before discharge. The RSPO as well as the environmental institutions in Malaysia under the Environmental Quality Act of 1974 mandate the release of POME with BOD content of not more than 100 ppm into the environment by palm oil mills (MPOB 2012). This regulation has prompted almost all the medium and commercial scales palm oil mills to treat their POME by anaerobic digestion to produce biogas to power the mills. The clear supernatant (with about 20–30 ppm BOD) from the digester after treatment could be recycled for fresh processing of FFB or irrigation in the plantation. The remaining portion of solid residues like EFB that do not feed the boiler during cogeneration in the palm mills are dumped at landfills which eventually release methane (which is a GHG) upon biodegradation. For economic and environmental sustainability for the oil palm industry, EFB could be co-digested with POME to produce biogas with high yield (about 25–32 % higher compared to POME digestion) and enhanced microbial biodegradability (Saleh et al. 2011; O-Thong et al. 2012).

The effective trapping of the biomethane-rich biogas is a challenge as most mills use the open pond for treatment and this has made Malaysian and Indonesian palm oil mills the two largest sources of methane emissions in the world (Saleh et al. 2011). Methane is a GHG which is found to be about 22 times more potent than CO₂ in trapping heat resulting in global warming. It is therefore paramount to ensure efficient treatment of POME to produce biogas for power generation and utilization as biofertilizer in the oil palm plantation. In a typical palm oil mill where POME is treated in open ponds, the POME generated from the processing 1 tonne of FFB per hour is able to produce about 333 m³ biogas which comprises about 65 % methane, 35 % CO₂, and traces of hydrogen sulfide (Ma 1999). This amount of POME can produce about 30–33 kW bioelectricity to add to the bio-energy generation capacity used in the mill.

More organized palm oil mills have been treating their POME using technologies such as flocculation, coagulation, decantation, ultrafiltration, flotation, aerobic, and anaerobic digestion. However, anaerobic, facultative, and aerobic digestion of POME in ponds for biogas production has been the common methods

for POME treatment in about 85–90 % of Malaysian palm oil mills. The technology for anaerobic digestion of biomass into biogas is previously described in [Chap. 2](#). For sustainable production of biogas from POME in palm oil mills, the following efficient methods can be applied:

- Existing open ponds could be converted to more efficient closed anaerobic digestion steel tanks integrated with biogas capture.
- Biogas produced from POME can be used to generate heat and power while the treated slurry can be used as fertilizer in the oil palm plantation.
- For efficient digestion, there must be consistent flow of effluent into the digester in which a constant temperature is ensured.
- Biohydrogen gas could be produced from POME by appropriate micro-organisms like *Clostridium Butyricum* instead of biomethane which is a GHG.
- Ensure regular maintenance and efficient operation of the digester.

Bio-hydrogen from POME (Leaño and Babel [2012](#)) is also a potential gaseous palm biofuel which can be integrated into the power generation unit of the palm oil mill. The utilization of plantation residues for biohydrogen production in an integrated palm biomethanol production system is discussed in the subsequent section. Figure [4.6](#) shows a proposed integrated system for sustainable production of heat, power, and biogas in palm oil mill.

4.4 Sustainable Practices for Integrated Palm Biofuels and Phytochemicals Production

Integrated systems for biofuel production are among the efficient ways of utilizing wastes for additional energy or other value added bioproducts. The method of integration of palm biofuels production has been reported by Gutiérrez et al. ([2009](#)) to contribute significantly to the economic and environmental sustainability of the palm biofuels industry.

Prior to the production of oil palm biofuels like biodiesel, the bio-oils (such as pyrolysis oil), the suitable palm feedstocks must first be produced and refined by appropriate technologies. The sustainability of these production processes may eventually affect the sustainability of the biofuels produced. Generally, the liquid and solid residues generated from the palm oil milling plants are found to be under-utilized. In order to maximize the sustainability of the industry as well as reducing fossil fuel consumption in the mills and refineries, solid palm wastes like PKS, PFAD etc. with high calorific values ([Chap. 1](#)) that are generated by the oil mills and refineries must be sustainably utilized for biofuels.

Palm biodiesel is commonly produced from two main types of oil palm feedstocks (mainly oils) namely (1) **first-generation oil palm feedstock** like CPO (Kansedo et al. [2009](#); Talukder et al. [2009](#); Raita et al. [2010](#); Hayyan et al. [2011](#); Man et al. [2013](#)), RBDPO (Shahbazi et al. [2012](#); Song et al. [2008](#)), CPKO

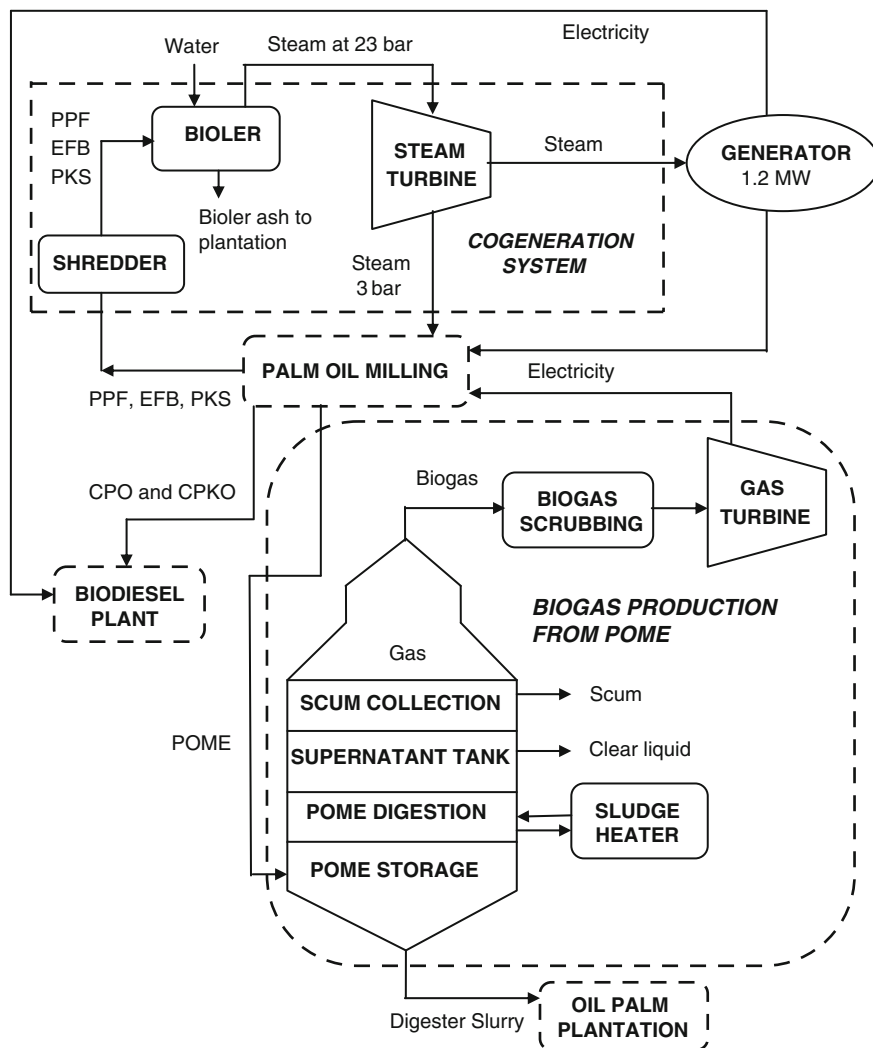


Fig. 4.6 Simultaneous production of biofuels from oil palm biomass within the palm oil mill

(Jitputti et al. 2006; Alamu et al. 2007; Alamu et al. 2008; Ojolo et al. 2011), and RBDPKO (Hui Ying 2008) and (2) *second-generation oil palm feedstocks* like pyrolysis oils from the solid residual components of the oil palm biomass such as EFB (Akhtar et al. 2010; Abdullah and Gerhauser 2008; Lim and Andréén 2011), PPF (Mazaheri et al. 2010), PKS (Kim et al. 2010; Salema and Ani 2012), PKC (Ngo et al. 2011), OPT (Deris et al. 2006), and OPF (Lim and Andréén 2011). Various methods of transesterification such as catalytic and noncatalytic (e.g., supercritical and subcritical transesterification) have been the basic means of converting the oils into alkyl esters or biodiesel. POME is also found to be an

efficient feedstock for biodiesel production (Hayyan et al. 2010). There are currently no reported works on biodiesel from OPR and OPL though they hold potential characteristics for efficient conversion into bio-oils or biodiesel. Though CPO and RBDPO have been the common types of feedstocks for palm biodiesel in the world, the recent palm biodiesel production outlook revealed the significant contributions from other palm feedstocks like palm olein (Boey et al. 2011; Choi et al. 2011), palm stearin (Lai et al. 2000), and PFAD (Cho et al. 2012; Chongkhong et al. 2007).

Commercially, biodiesels produced from the bio-oils from PKS, OPF, EFB, PPF, OPT, and PKC have not been realized though they are high potential sources for sustainable production of palm biodiesel. In most cases, the pyrolysis oils are used for other fueling purposes or for bioelectricity generation. The sustainable production of palm biodiesel entails efficient oil palm agricultural practices, efficient utilization of the oil palm biomass for CPO and CPKO production as well as their subsequent conversion into biodiesel in ways which adhere to the basic principles of sustainable palm biodiesel production.

The FFA and other impurities in the CPO and CPKO are removed during the refining processes hence RBDPO and RBDPKO would be directly transesterified into biodiesel. Choo et al. (1992) have used CPO, CPKO, palm stearin, and palm olein as direct feedstocks for biodiesel production in a 3000 tonne pilot plant without pretreatment using the method of co-esterification and transesterification employing an appropriate catalysts. This process is found to be energy efficient as the temperature requirement for the reaction is less than 100 °C and the washing stage is also eliminated. The biodiesel produced by this method is able to achieve a minimum of about 96.5 % yield with its quality meeting the European standard on biodiesel (EN 14214) (Duarte et al. 2007). The properties of the biodiesel produced from CPO by this method indicate that it can be used directly in diesel engines without modification with no engine knocking (Choo et al. 2002). The emissions from the combustion of this high flash-point diesel (about 174 °C compared to 98 °C for petroleum diesel) were observed to be much cleaner with no explosive fuel vapor (Choo et al. 2002). Table 4.3 summarizes the physico-chemical properties of palm biodiesel compared to petroleum diesel. The product's quality is of utmost importance for sustainability. Biofuels produced from oil palm biomass must meet the highest quality standards. The calorific value, flash point, and cloud point of palm biodiesel is lower than those for petroleum diesel. However, the higher cetane number of the palm biodiesel is an advantage, as it possesses good combustion quality hence energy efficient compared to petroleum diesel (Duarte et al. 2007). Again, the viscosity of palm biodiesel is higher thus possessing a higher volatility compared to petroleum diesel. Another important parameter for an efficient biofuel is the fuel consumption rate for which oil palm biodiesel is found to be closely related to that of petroleum diesel.

With the goal of achieving sustainable biofuel production from oil palm biomass, integrated biofuel plants have been developed with efficient technologies of utilizing the wastes from the various processes involved in palm oil biofuels. Currently in Malaysia, almost all the over 18 licensed biodiesel production plants

Table 4.3 Specifications and characteristics of palm biodiesel

Fuel property	Biodiesel standards		Palm biodiesel	Petroleum diesel	B5 palm diesel ^a
	EN 14214	ASTM D6751			
Fuel source			Bio based	Fossil based	Bio/fossil based
Calorific value (MJ/l)	–	–	31.0	46	–
Ester content (wt%)	>96.5	–	878.3	–	841.9–845.9
Heat of combustion (MJ/kg)	–	–	0.040	0.046	–
Cetane number	<51	<47	58–65	53	51–57
Pour point (°C)	–	–	15–16	15	–
Flash point (°C)	<120	<130	174	98	75–81
Cloud point (°C)	–	–	15–16	18	14–16
Density at 40 (°C) (kg/m ³)	860–900	–	878.3	823.0	–
Viscosity at 40 (°C) (cST)	3.5–5.0	1.9–6.0	4.4–4.5	4	4.1–4.5
Sulfur content (wt%)	>0.001	>0.0015	0.04	0.10	0.00017
Sulphated ash content (wt%)	>0.02	>0.02	>0.01	–	–
Carbon residue (wt%)	>0.3	>0.50	0.02	0.14	0.2
Acid value (mg KOH/g)	>0.5	>0.80	0.08	–	–
Iodine value	>120	–	52	–	–
Water content (mg/kg)	>0.05	>0.05	>0.05	–	>0.001
Monoglyceride content (wt%)	>0.8	–	>0.4	–	–
Diglyceride content (wt%)	>0.2	–	>0.2	–	–
Triglyceride content (wt%)	>0.2	–	>0.1	–	–
Free glycerol content (wt%)	>0.2	>0.2	>0.01	–	–
Total glycerol (wt%)	>0.25	>0.24	>0.01	–	–
Phosphorus content (mg/kg)	>10	>10	–	–	–
Distillation temperature (90 % recovered, °C)	–	>360	–	–	363.7–367.8

^a B5 palm diesel: 5 % palm biodiesel mixed with 95 % petroleum diesel

(with about eight operating on commercial basis) operate using the patented method developed by Choo et al. (1992) for the integrated system for co-production of biodiesel and phytochemicals from CPO. The use of RBDPO, however, eliminates the esterification process prior to transesterification.

Biodiesel production from high FFA feedstocks like palm olein and PFAD by the process of esterification with acid catalyst and transesterification at low temperatures have also been demonstrated by several researches (Cho et al. 2012; Boonnoun et al. 2008; Chongkhong et al. 2007). PFAD in particular presents a cheap source of second-generation palm biodiesel feedstock which is available in significant quantities. Malaysia alone produces about 700,000 tonnes/year of PFAD as a by-product from the refining processes (MPOB 2010). Due to the limited uses of PFAD, oil palm refiners currently trade it at higher discounts (between USD 100 and USD 690 per tonne) compared to CPO and RBDPO so that biodieselers could utilize them and eventually add to the economic sustainability

of the oil palm refineries. In 2009, Indonesia began PFAD biodiesel production in the world's first continuous commercial scale palm biodiesel plant of about 200 tonnes/day production capacity (Cheah et al. 2010) which is capable of achieving almost 100 % biodiesel yield. With this continuous process, multifeedstocks (crude bio-oils from oil palm biomass) like pyrolysis oil, CPO, and CPKO could be incorporated into the feed entry line for single processing.

CPO contains a lot of phytochemicals such as phenolic compounds, carotenes, vitamins E, sterols, squalene, phospholipids, co-enzyme Q10 etc (Ofori-Boateng and Lee 2013; Lee and Ofori-Boateng 2013) which are lost during the refining process. For a sustainable biodiesel production from CPO using the method reported by Choo et al. (1992), these phytochemicals could be recovered before it is sent to the biodiesel unit in order to add more value to the biodiesel produced. Alternatively, the biodiesel produced is distilled in a short-path evaporator in order to concentrate the phytochemicals in the bottoms which are further purified. In Malaysia for instance, the Malaysian Palm Oil Board (MPOB) have developed potential technologies for recovering these important bioactive substances from palm oil biodiesel at high purity. For every tonne of palm oil biodiesel combusted, about 2.41 kg of phytochemicals is also lost which would have added about USD 970 (Choo et al. 1992) to the profits of the plant. Malaysia and Indonesia are currently producing biodiesel from PFAD with phyto-chemicals recovery systems. Like CPO, PFAD is found to contain about 0.5 % vitamin E, 0.4 % phytosterols, and 0.8 % squalene (Bonnie and Mohtar 2009).

The conventional or inorganic methanol and catalysts used for biodiesel production are costly thus adding more economic constraints to the biodiesel production cost resulting in expensive final product. Ashes from EFB is reported to be a good source of material for preparing green catalysts for biodiesel production (Yaakob et al. 2012). As a way of adding economic and environmental values to the oil palm biodiesel industry, the production of biomethanol (or bioethanol) and biocatalysts (from solid residues like EFB) could be integrated into the biodiesel production plant. EFB, OPF, and OPT have high sugar contents which could be fermented into bioethanol. On the other hand, the cellulose and hemicelluloses of these biomass could be hydrolyzed and fermented into bioethanol with high yields. By means of producing bioethanol from the solid residues (lignocellulosic contents of oil palm biomass have been outlined in Chap. 1) generated by the oil mills and plantation for transportation fuel purposes, phytochemicals could also be extracted during the pretreatment process. This would add more economic value to production cost of both the bioethanol and phytochemicals. Figure 4.7 shows the schematic flow diagram of the integration of bioethanol and phytochemical production into the biodiesel production plant for sustainable oil palm development.

The co-production of biodiesel and bioethanol from oil palm biomass has been demonstrated by Gutiérrez et al. (2009). The common feasible types of palm feedstocks for bioethanol production are EFB (Millati et al. 2011), OPF (Zahari et al. 2012), PKC (Jørgensen et al. 2010; Yan et al. 2009; Cerveró et al. 2010), and OPT (Jung et al. 2011). The integration of materials and energy flows between biodiesel and bioethanol production flows has been reported to record a decrease in

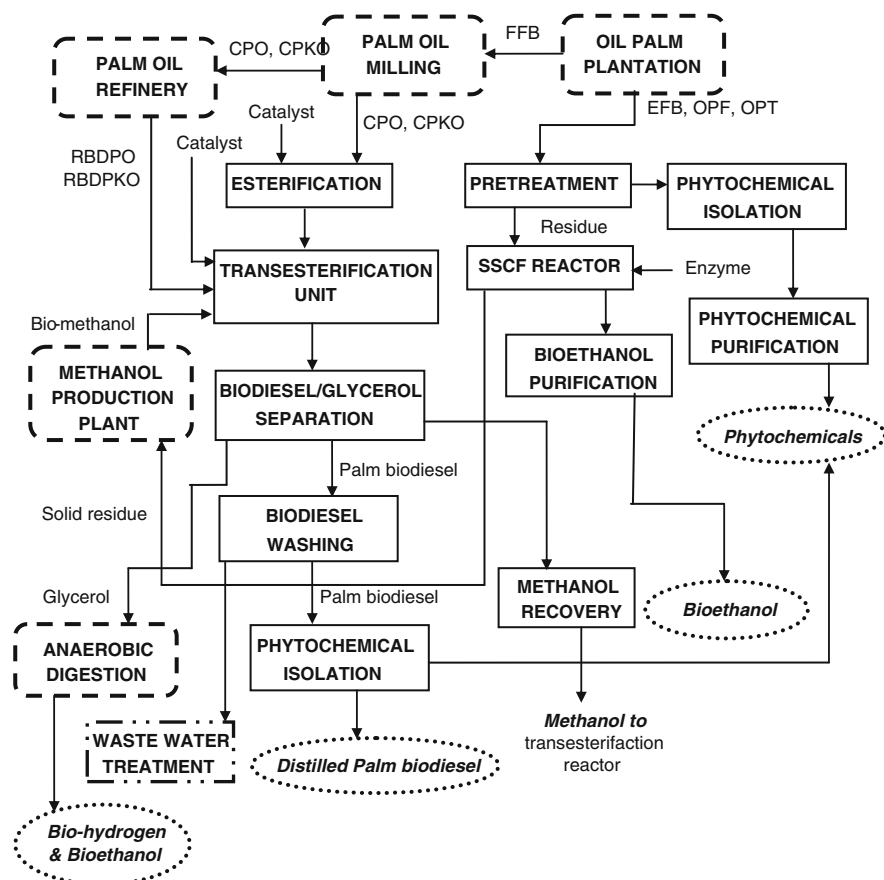


Fig. 4.7 Schematic flow diagram of the integration of biodiesel, bio-methanol, and bioethanol production from oil palm biomass

unit energy cost by 39.8 % (Gutiérrez et al. 2009). This cost would be much lower if the excess energy produced from the palm residue cogeneration plant in the palm oil mill is sent to the biodiesel–bioethanol plants for economic sustainability. The lignin obtained as by-product from the bioethanol production plant can be directed into a biosyngas production plant for bioelectricity production.

Within the integrated system for the co-production of oil palm liquid biofuels, energy efficiency (heat integration) as well as better environmental considerations would help improve the sustainability or performance indicators of the plant. During the process of distillation, the column bottoms especially water streams could be recycled or recirculated for other processing activities like pretreatment of the biomass for bioethanol production.

Again, bioethanol obtained after biodiesel purification can also be recycled and reused for transesterification reaction. Gutiérrez et al. (2009) reported that the

utilization of energy from the overhead vapors of distillation columns improves the integrated system by cutting down the ‘energy’ consumption significantly. Hot streams must be used to heat cold streams by which the technology of pinch analysis could have been used to facilitate energy savings within the integrated system. Grisales et al. (2005) have also studied the efficiency of azeotropic distillation for the dehydration of ethanol using heat integration method.

Though the cost of bioethanol from sugarcane and corn⁸ is almost half that produced from lignocellulosic materials, heat, and materials integration coupled with government incentives would help achieve better efficiencies and product price. Other ways of improving the bioethanol production process include efficient process and equipment design by the appropriate engineers; the research and development intensification for high stability and efficient enzymes for simultaneous saccharification and co-fermentation (SSCF)⁹ on commercial basis; reduction in overall ‘energy’ consumption.

4.5 Sustainable Production of Bio-syngas and Biomethanol from Oil Palm Biomass: A Possible Integration into Palm Biodiesel Production Plant

The production of biosyngas from the solid components of the oil palm biomass such as EFB, PPF, OPT, OPF, etc. through gasification have been reported (Bula et al. 2012; Kelly-Yong et al. 2011; Nipattummakul et al. 2012). Hishida et al. (2011) have achieved conversion efficiencies of about 98 % and 94 % for the gasification of EFB and PKS into clean biosyngas, respectively, using an entrained-flow gasifier which was developed by the Mitsubishi Heavy Industries Ltd. (MHI) in Japan. The biosyngas is scrubbed or purified before it is fed into a gas turbine for power generation or directly synthesized into biomethanol for other purposes.

In a plant where biosyngas is produced from natural gas for subsequent methanol production, the integration of oil palm biomass gasification for biosyngas and biomethanol can help reduce cost and eventually save the environment.

Again, POME treatment for biomethane can also be integrated into the syngas production plant where the methane can be converted into biomethanol directly. Again, the glycerol from the biodiesel production unit could be co-gasified with the biomass in the biosyngas unit for enhanced biosyngas production (Skoulou and Zabaniotou 2013).

The solid residues of the oil palm biomass is first pretreated by drying and pulverization before steam gasification. Through the technology of pressure swing

⁸ The cost of bioethanol from corn, sugarcane and lignocellulosic materials are USD 0.88, USD 0.82 and USD 1.50 respectively (McAloon et al. 2000; Quintero et al. 2008).

⁹ SSCF process for bioethanol from lignocellulosic materials through various integrated schemes is found to have the best energy performance (Gutierrez et al. 2009).

adsorption, the air from the atmosphere could be separated into clean oxygen and hydrogen where the oxygen could be used during the gasification process. The gasification of the fibrous biomass like EFB, OPF, and OPT is found to be faster compared to that for PKS though their conversion efficiencies are excellent (Nipattummakul et al. 2012). Steam gasification of OPT is reported to yield lower biosyngas at gasification temperature below 700 °C (Nipattummakul et al. 2012). For environmental sustainability, the biosyngas is purified through dust removers, scrubbers, and multi-component adsorption tower in order to obtain clean biosyngas. Biosyngas can be used as feedstock for the production of various chemicals and fuels like biodiesel, biomethanol, hydrogen gas etc. by the BtL process (Fischer–Tropsch). Figure 2.6 summarizes the biomethanol production from biosyngas.

4.6 Integrated Bio-oil, Biohydrogen, and Biogasoline Production from Oil Palm Biomass

During the production of biogasoline from palm oil or pyrolysis oil from palm biomass, hydrogen (mostly fossil-based) is used to facilitate the conversion process. Figure 2.1 (Chap. 2) shows the process flow of biomass conversion into bio-oil via simultaneous cracking and hydrogenation. Figure 2.10 (Chap. 2) can also be used for the direct production of biogasoline from biosyngas. This unit can be integrated into the production of biogasoline from CPO or CPKO (Fig. 4.8). Biokerosene from CPKO is reported to be a potential cost-effective biofuel in the near future (Llamas et al. 2012). Currently, biofuels from CPKO has not gained much attention and about 90 % of the CPKO are sold to the oleochemical industry. The palm kernels that are not cracked for oil but are dumped at landfills can be explored for biokerosene production in order to improve the oil palm biofuel industries economically and environmentally.

From Fig. 4.8, the biohydrogen which is used in the liquid-phase reaction of the palm bio-oil can be sourced from the biosyngas production plant after the water shift reaction (see Fig. 2.12, Chap. 2). Again, biohydrogen that is generated from POME and EFB can also be directed to the system for biosyngas conversion into biohydrogen and directly into the liquid-phase reactor. The pyrolysis oil together with CPKO or CPO are then pretreated in a single reactor and distilled afterward to obtain biogasoline. The feasibility of using oil palm biomass for the production of biosyngas (Konda et al. 2012; Atnaw et al. 2011), biohydrogen (Inayat et al. 2012; Chong 2009), biogasoline (Nasikin et al. 2009) have been assessed by various researches. Best management practices for sustainable palm biofuels production are outlined in Sect. 4.8.

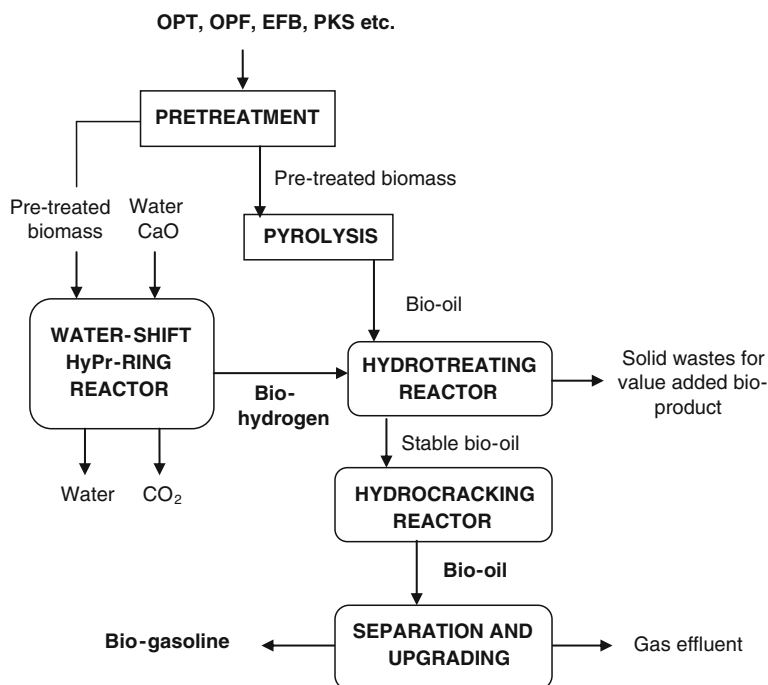


Fig. 4.8 Schematic flow diagram of an integrated system for bio-oil, bio-hydrogen, and bio-gasoline production from oil palm biomass

4.7 Second-Generation Solid Biofuels from Oil Palm Biomass

Presently, the major feedstocks for the production of solid palm biofuels on commercial scale include EFB, PKS, PKC, PPF, OPF, and OPT. Palm briquettes (Husain et al. 2002), torrefied palm biomass (Uemura et al. 2013; Lu et al. 2012), and palm pellets (Razuan et al. 2011) are the main types of palm biofuels on the market. In most traditional settings, PKS is directly combusted to produce heat for various purposes like gold melting, cooking etc.

In the briquetting plant, the biomass is processed into long strands of fibers and dried to reduce the moisture content to at most 15 %. The dried fibers are then ground and compressed into denser forms commonly called briquettes with various shapes and sizes mostly 30–35 cm in length and 9–10 cm in diameter (Husain et al. 2002). Multi-feedstocks like EFB and PKS that are briquetted together is able to improve the energy content of the briquettes (with calorific value of 17–19 MJ/kg). Oil palm briquettes presently have good market thus adding more economic value to the palm biofuels.

Apart from producing briquettes from oil palm biomass, charcoal which could be used for efficient boiler firing can easily be made from PKS by carbonation. In a controlled operation parameters, PKS is converted into PKS charcoal in carbonization kilns. Most companies involved in PKS carbonization with special technologies are able to produce energy-efficient biofuels within a short carbonation time which is able to reduce the energy consumption of the production plant.

Oil palm biomass pelleting is also done to produce solid biofuels in the form of pellets that are used in place of coal for firing boilers, furnaces, foundries, kilns etc. Oil palm pellets of about 6–12 mm have high calorific value (17–18 MJ/kg) and low moisture content (<10 %).

4.8 Best Management Practices for Sustainable Palm Biofuels Production

The consumption of palm biofuels also plays an important role in the route to sustainable development ([Chap. 1](#)). Because biofuels are currently costly, they cannot be used without blending. Policy makers must mandate the use of biofuel blends (as most countries are doing now) and also put in place the needed strategies like incentives and subsidies which would encourage the mass in consuming biofuels for safe environment.

The biorefinery must be sited closer to the source of feedstock. For instance, as indicated already, almost all the large-scale palm oil mills have integrated electricity production from the solid residues. This makes the whole integrated system energy efficient and environmentally friendly as fossil fuel combustion is limited with relation to transportation as the plant is sited within the palm oil mill. Again, the compost and mulch from the palm wastes are easily accessible by the plantation operators when the palm oil mill is sited very close to the plantation. The overall energy usage within all the biorefineries must be monitored from time to time in order to ensure the efficiency of the plant. For instance, the processes of distillation and evaporation as well as heat exchanging can be done using multiple effect evaporators and distillation columns so that heat integration (usually via Pinch technology) between the individual condensers and reboilers would help reduce hot and cold utilities requirement hence reducing energy consumption (Franceschin et al. [2008](#)).

In the bioethanol production unit, the fermentation stage can be improved by decreasing the fermentation temperature to increase sugar and bioethanol yields which would eventually increase the purity of the bioethanol. Laid down principles and management practices to improve palm biofuel production plants must be reviewed regularly to meet the current sustainable palm production principles.

For social sustainability of palm biofuels (discussed into detailed in [Chap. 8](#)), employers must ensure safe and fair working conditions for all the employees. Good salary as well as incentives would motivate workers. Communities nearby

could be engaged in the development of the biorefinery whereby training programmes could be organized for them periodically to brief them on best management practices for sustainable palm biofuel production. In order to ensure the safety of workers, safety precautions must be observed while periodic seminars on occupational safety must be organized to update workers.

Palm biofuelers who are not engaged in the palm feedstock production must ensure that their feedstocks especially CPO, CPKO, RBDPO, and RBDPKO are obtained from certified producers who follow sustainable criteria set by the RSPO. Biofuelers must site their production plants very close to their feedstock suppliers as well as the market for their products. Transportation to these markets must be efficient to ensure reduced emissions of fossil fuel combustion. Biofuel production plants that utilize the oil palm wastes like EFB, OPF, OPT, PPF, PKS etc. must design their plant in a more flexible way to ensure multi-feedstock entry. For instance, the system for the gasification of EFB for biosyngas must be able to gasify the other types of wastes for the same product recovery.

As explained already, integration of the production of different biofuels is able to ensure sustainability for the whole system as wastes from one plant can be utilized for other products in another plant. The production plants must, therefore, be designed to produce and utilize efficient co-products in a more economical and environmental ways. The wastes that are generated after utilizing all the oil palm biomass for biofuel production must be treated before discharge. The slurry from POME treatment, ashes from the biolers, gasifiers, pyrolysis reactors etc. must be sold in order to add economic value to the palm biofuel plant as these wastes cannot be used again to produce any other biofuels. This management practice would lead the industry to zero wastes or discharge which is a step toward sustainable development for the oil palm biofuel industry.

The oil palm biofuel industry could be designed in such a way that the source of energy for powering the whole plant from the feedstock production line to the biofuel line could be attained from the industry itself. The energy generated by the palm oil mill is more than what is needed by the plant, hence the remaining could be directed to the biorefineries or nearby industries for cost-effective production. If the biofuel industry is independent on the feedstock production, glycerol can be used to generate electricity (Zhang et al. 2012; Sharma et al. 2011) to subsidize the amounts of fossil fuels used by the plant. On the other hand, biofuelers could buy green power from the palm oil millers or probably utilize the plantation wastes like OPF for fuel production. Other renewable energy sources that could be used include solar energy via solar photovoltaic.

Another way to ensure energy efficiency within the biorefineries is to carry out energy audit regularly for improved energy usage. The production plant efficiency must also be increased in order to reduce the overall energy consumption.

The use of large amount of water in the biorefineries could lead to the generation of wastewater that would require lots of energy and materials to treat as it would be environmentally unsustainable to discharge untreated wastewater into the environment. Water use during biofuel production must be minimized through plant design efficiency. Dry cleaning systems for pretreatment of feedstocks which

conventionally requires less water must be encouraged to improve the process by minimizing product losses and water consumption (Dias et al. 2011). There must also be regulations that govern the release of wastewater into the environment at specified chemical properties. The levels of oils, total suspended solids, toxic materials, metals as well as the biological oxygen demand (BOD), chemical oxygen demand (COD), and pH of the wastes water must be checked to ensure they are in their right amounts before discharging. Biofuelers who do not have the facilities to treat their wastewater must discharge them to nearby wastewater treatment plant or send them commercial composting plants for further utilization. In all distillation units, water could be condensed and reused. Emissions like excess heat, particulate matter, and other gases must be trapped before discharging into the environment. The use of efficient equipment would help minimize excess heat emissions and improve the energy efficiency of the plant.

4.9 Global Production and Consumption Statistics of Palm Biofuels

The five major contributors of palm biodiesel in the world today are Indonesia, Malaysia, Thailand, Colombia, and South Korea with Indonesia being the largest producer and exporter. The world's palm biodiesel production capacity in 2012 was at about 4.24 billion liters which was about 1 % the total biodiesel production capacity in the world in 2012 (MPOB 2012). In 2008, Malaysia and Indonesia contributed about 2 billion liters and 0.6 billion liters of palm biodiesel in the world, respectively, representing about 96 % of the total amount of palm biodiesel produced in 2008 (MPOB 2012). The percentage exports were as low as 3–4 % of the total produced palm biodiesel in 2008. United States of America (USA) and Europe have been the major importers of Malaysia and Indonesia's palm biodiesel since 2006 making them extract over 80 % of the total exports (MPOB 2012).

Indonesia and Malaysia together plans to produce about 7.1 billion liters of palm biodiesel every year (Sani 2009) and consume a greater portion of it by themselves as their governments are mandating B15 blends with petroleum diesel by 2020. Malaysia was the leading producer of palm biodiesel in 2005 but began to loose their first place to Indonesia in 2010. In 2006, Malaysia commissioned its first normal and winter-grade commercial palm biodiesel production plant (i.e., Carotino Sdn Bhd) with total capacity of about 0.106 billion liters (MPOB 2011). Up to date, about 61 palm biodiesel plants are in operation (about 30 production plants are yet to start operation) in Malaysia with total production capacity of about 0.21 billion liters per year. Today, the world's biggest biodiesel plant is in operation in Singapore which produces about 0.941 million liters of palm biodiesel a year (MPOB 2011).

In 2011, out of the total palm biodiesel installed capacity of about 3.2 billion liters from about 26 production plants, Malaysia produced only about 0.2 billion liters (MPOB 2011). In 2011, Indonesia produced about 1.52 billion liters of palm

biodiesel, about 1.35 billion liters are exported with Europe being the single largest market contributing about 39 % of European biodiesel imports. By the end of 2013, palm biodiesel export is projected to increase to about 1.5 billion liters (MPOB 2011). In Indonesia, in 2012, about 26 palm biodiesel production plants with total installed capacity of about 4.28 billion liters contributed about 1.8 billion palm biodiesel to the world's production capacity (MPOB 2012). Presently, Indonesia consumes only about 10 % which is not encouraging. Because the Indonesian government mandates the consumption of biodiesel, there are ongoing initiatives to increase palm biodiesel to about 700 million liters (i.e., over 400 % of the present consumption) by the end of 2013. However, the Indonesian government intends to provide biofuel subsidies at about USD 0.3119 per liter biodiesel and about USD 0.3638 per liter bioethanol by 2013.

Presently, though Indonesia's bioethanol production from molasses is projected to increase to about 20–30 million liters by 2013, there is no company that produces cellulosic ethanol from oil palm biomass. In the world today, there exist no company producing bioethanol from oil palm biomass due to process sophistication and large capital investment.

The common type of palm gaseous biofuel produced in the world currently is biogas from POME and EFB. In Indonesia alone, about 350,000 tonnes of biomethane was produced from about 34 million m³ in 2006. In 2007 and 2010, Malaysian palm oil mills collectively generated about 54 million cubic meters and 57 million cubic meters of POME, respectively, which were able to generate about 1.5 billion cubic meters and 1.6 billion cubic meters of biogas, respectively, (NKEA 2011). However, when this biomethane from the POME is vented into a CHP system, about 600–665 MW energy can be generated for other purposes. In Malaysia, currently, about 138 MW CHP capacity facilities are installed for biogas transformation into electricity and heat. Biohydrogen and biosyngas from solid palm residues are not on commercial scale production but under research and development on pilot and small scales. Though the technology of producing biogas is readily available in Malaysia and Indonesia, only about 6 % of the total palm oil mills in both countries treat their POME and EFB for biogas production. This percentage is able to generate about 810 MW clean electricity which could be utilized within the palm oil mills (NKEA 2011).

4.10 Conclusion

Various authors have demonstrated the feasibility of utilizing oil palm biomass for all the three types of biofuels. However, the management practices involved in oil palm biomass production as feedstock for palm biofuels are energy intensive, environmentally unfriendly, and cost-ineffective. This chapter has outlined sustainable management practices which would help improve the energy efficiency, economic, and environmental impacts associated with palm biofuels production. The possible integration of multiple feedstock treatment and process technologies

for different kinds of palm biofuels have been elaborated in this chapter. Palm biofuels production would be sustainable when best management practices are used throughout the life cycle of the biofuel.

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Part III
Sustainability Assessment of Biofuel
Production from Oil Palm Biomass

Chapter 5

Environmental Sustainability Assessment of Biofuel Production from Oil Palm Biomass

Abstract With the aim of minimizing the dependency on fossil fuels whilst improving the economic viability and environmental performances of oil palm production for biofuels production, emission control from these systems become invincible. However, with best management practices couples with stringent adherence to basic environmental sustainability principles, these hurdles may be surmounted. The environmental sustainability dimension of impact assessment for this chapter is based on life cycle assessment for common palm biofuels like biodiesel, bioethanol, bio-methanol via BtL route, biogas and bio-electricity from oil palm biomass. Possible improvement options are also outlined in this chapter to ensure more positive energy balance and almost zero emissions from each of the biofuels production systems considered.

Keywords Life cycle assessment • Greenhouse gas emissions • Palm biofuels • Bioelectricity • Environmental sustainability • Climate change • Energy balance

5.1 Introduction

Since the ecosystem is a closed one, the damage caused to one part of it may have direct impact on the other parts thus the need to promote environmental sustainability to ensure minimal detrimental effects for healthy living. Daly (1990) defines environmental sustainability as the indefinite rate of renewable resource harvest, pollution control and non-renewable resource depletion. In other words, through the act of meeting the current and future generations' resources and services' needs without compromising the health of the ecosystem, the environment becomes more sustainable. Again, for a system to be considered environmentally sustainable, the amount of wastes generated from that system must not exceed the input resources as well as the wastes that the environment can carry. This is normally achieved by minimizing the consumption of non-renewable resources like fossil fuel. In an environmentally sustainable system, the human welfare is

satisfied without destroying biological diversity or exceeding its ecosystem's capacity to regenerate the important goods and services. Again, in an environmentally sustainable system, processes are carried out in a uniformly indefinite continuity with insignificant impact on the environment which eventually renders the system's surrounding (or ecosystem) intact for the benefit of the future generations.

Many are the environmental challenges associated with oil palm cultivation and palm oil production for biofuels and food applications. Some of the environmental challenging factors facing the palm biofuels industry include the massive emissions resulting from the production of the raw materials; type of production technologies employed; amount of input resources used to obtain the overall products; waste management practices; pollution control etc. The cultivation of oil palm biomass is a potential contributor to waste generation, air, water and land pollution, which have damaging effects on the environment if best management practices for sustainable production are not adhered to. In the plantation, for instance, the clearing of new forests and the conversion of peat lands for oil palm cultivation lead to biodiversity loss and rise in greenhouse gas (GHG) emissions because of fossil fuel combustion and decomposition of organic matter in peat lands. The contribution of environmental impacts from palm oil cultivation would eventually add to the rise in the environmental contributions from the production systems of palm biofuels. Therefore, there is a greater need to minimize environmental emissions from the feedstock production units. In the palm oil mills, the efficient management of wastes generated by the mills in the form of palm oil mill effluent (POME), empty fruit bunches (EFB), palm pressed fiber (PPF), palm kernel shells (PKS) and palm kernel cake (PKC) is a great challenge as only a few of the wastes are utilized to generate electricity for use within mills.

The Roundtable for Sustainable Palm Oil (RSPO), the national biofuel policy (in Malaysia) as well as the Kyoto protocol have come to play a vital role in ensuring the reduction of potential emissions like GHGs from the oil palm industry by strategically spelling out principles and criteria for sustainable oil palm production. The oil palm industry in Malaysia has been part of the United Nations Framework on Climate Change (UNFCCC) under the Kyoto Protocol since 2004 with the aim of reducing GHG emissions from the industry. In view of this, many carbon reduction projects under the Clean Development Mechanism (CDM) are ongoing with the hope of achieving the environmental sustainability principles set by the RSPO and the government of Malaysia. CDM projects in Malaysia and Indonesia's oil palm industries are focused more on afforestation and 'wastes to value added bio-products' especially bioenergy and bio-composts in order to minimize GHG emissions. In Indonesia, the CDM projects in the palm oil mills have successfully installed about 9.7 MW Combined Heat and Power (CHP) plants for bio-electricity generation from PKS and EFB to replace the diesel powered generators (MPOB 2010).

Life cycle assessment (LCA) has been the commonest environmental impact assessment tool used to evaluate the production of biofuels over their life cycles. The LCA GHG emissions of first generation biofuels like biodiesel from crude

palm oil (CPO) depends largely on the feedstock production (Wicke et al. 2008) and the production location (Stephenson et al. 2010). Thus, the adherence to responsible management practices during feedstock agriculture is very important for environmental sustainability of biofuels. Though the combustion of biofuels result in GHG emissions savings compared to fossil-based fuels, their production processes release significant amount of GHGs that jeopardize the environmental sustainability of the biofuels themselves. For instance, the combustion of bioethanol obtained from corn stover and switch grass have been assessed based on LCA to have GHG emissions reduction of 82–84 % (Levelton 2000) and 75–96 % (Spatari et al. 2010) respectively compared to gasoline. In this chapter, environmental impacts of palm biofuels like biodiesel, bioethanol, bio-methanol and biogas production systems are assessed based on Malaysian's oil palm production conditions.

5.2 Environmental Sustainability Assessment: Overview

One major strategy for ensuring environmental sustainability of a system is to periodically carry out environmental impact assessment (EIA) of the system or product over its life cycle. During such assessments, many factors are critically considered which include efficient design of processes and products, selection/choice of raw materials that maintain biological diversity or natural resources, reuse and recycling of co-products, review and assessment procedures for raw material use and wastes generation, improvement in energy efficiency of the system etc.

Environmental Impact Assessment is a systematic method for identifying, evaluating and analyzing the major environmental effects of a production process throughout the life cycle of its product. Table 5.1 summarizes the major environmental effects that are assessed during EIA to ensure the overall environmental sustainability of the system. Many environmental assessment tools and techniques that effectively quantify environmental effects have been used by many researches. These tools include life cycle assessment (LCA) (Rebitzer et al. 2004; Pennington et al. 2004), life cycle sustainability assessment (LCSA) (Heijungs et al. 2010), life cycle commonality metric (LCCM) (Wang and Tseng 2009), environmental risk assessment (ERA), eco-efficiency, ecological footprint analysis (EFA), material flow analysis (MFA) (Rockström et al. 2009), resource accounting, national accounting matrix including environmental accounts (NAMEA) etc. For a clearer evaluation of the environmental impacts of a product or process in order to effectively assess and justify its environmental sustainability, any two or three of the environmental tools mentioned above can be used together (e.g. LCA and LCC). This chapter focuses on LCA as the environmental tool to assess the environmental sustainability of palm biofuels.

Environmental Risk Assessment is an environmental impact assessment tool used to identify and evaluate the negative impacts of a particular technology or

Table 5.1 Summary of environmental impact categories that determine the environmental sustainability of a production system

Environmental impact category	Characterization factors
1. Climate change	Global warming, fossil fuels, greenhouse gas (GHG), ocean acidification, global dimming
2. Biodiversity loss	Wildlife species extinction, poaching, endangered species, pollinator decline
3. Air quality change	Air pollution, smog, tropospheric ozone, volatile organic compound (VOC), atmospheric particulate matter, electromagnetic radiation,
4. Water use and water quality change	Water pollution, eutrophication, ecotoxicity, urban runoffs, oil spills, marine debris, waste-water, marine pollution, micro-plastics
5. Land use and land degradation	Slash-and-burn (bush burning), land pollution, desertification, overgrazing, monoculture, pesticide leaching potential, habitat fragmentation, habitat destruction, urban sprawl
6. Soil degradation	Soil erosion, soil contamination, soil salinity
7. Energy use	Energy balance, efficiency in energy use, renewable energy use,
8. Waste and chemicals emissions	Landfills, incineration, waste disposal incidence, herbicides and pesticides drifts, dioxins,
9. Resource use and depletion	Deforestation, illegal logging, over-use of natural resources,
10. Ozone depletion	Chlorofluorocarbons (CFC), ultraviolet exposure
11. Nuclear emissions	Nuclear fallout, nuclear weapons, nuclear radiations, high level radioactive waste emissions,
12. Nanotechnology impacts	Nano-pollution
13. Human toxicity	Heavy metals, respiratory organics, respiratory inorganics,

The main environmental considerations for the LCA studies in this chapter are listed and elaborated in Appendix F

human activity on the ecosystem. ERA finds its applications in policy regulations and decision-making, product labeling and safety as well as in the evaluation of risk reduction measures in manufacturing industries. The European Union System for the Evaluation of Substances (EUSES), EcoFate, Exposure Model for Soil-Organic Fate and Transport (EMSOFT) are the common tools and softwares for carrying out ERA.

Eco-efficiency is another environmental impact assessment tool used to maximize the efficiency of a production system and at the same time paving ways to reducing the negative impacts on the environment. This assessment tool is mostly used to link the economic output of the system to the environmental impact of the product or production process via LCA. Though Eco-efficiency does not show the long term sustainability of the product, its results are helpful in selecting, comparing and evaluating the economic and environmental market potentials of the product under study hence helping in good decision making.

EFA is an environmental sustainability tool used to compare human demands on the ecosystem with the capacity to regenerate new resources. In other words,

EFA is able to quantify the consumption rate of resources and compare the results with the nature's ability to provide that amount of resource consumption. This assessment method is quite similar to LCA's energy balance and this is useful in policy making by examining whether a system utilizes more than what it has in its surrounding. There are various EFA calculators developed by Non-governmental organization (NGOs) and research centers and these are able to quantify consumption of resources in normalized land area called global hectares (*gha*).

MFA also called Substance Flow Analysis (SFA) is one other method for systematically assessing the flows and stocks of materials (including checking mass balance, sensitivity and uncertainties) within the system at a particular point in time in a quantitative manner (Rockström et al. 2009). MFA is commonly applied in industrial ecology for creating best industrial practices, controlling process flow of materials and for creating consistent patterns in energy use. In environmental management and engineering, MFA is used to design strategies for air pollution control, waste management and nutrient management in soils. MFA and LCA are linked in one way or the other in that MFA is used to establish an inventory for LCA. MFA methodology include system boundary definition, process chain analysis using accounting and mass or material balancing and finally evaluation stage that may include impact criteria.

5.3 Environmental Sustainability Assessment via Life Cycle Assessment

Life Cycle Assessment is an environmental assessment tool used to model (evaluate and quantify) the impacts of a product over its life cycle (i.e. from extraction of the raw materials through materials conversion, product formation, product distribution and use, disposal or recycling of the product and finally to the intervening transportation stages). LCA is one of the effective tools for evaluating the environmental feasibility and sustainability of fuels. Normally, LCA results and evaluation methods for multiple feedstocks and production technologies include the net energy and material balance calculations (Schmer et al. 2008). However, the main goal of LCA is to compare the full range of environmental damages assignable to products, services or processes in order to choose the least harmful one with ease. Again, LCA has been one of the important tools used in strategizing business activities, improving on research and development, labeling products for marketing, public policy making as well as aiding in process and product design (Udo de Haes et al. 1999). Many governmental legislatures like the United States Environmental Protection Agency (EPA) use this tool to assess the environmental impacts of various production systems.

There are two main types of LCA namely accounting or attributional life cycle assessment (ALCA) and consequential life cycle assessment (CLCA) (or effect-oriented LCA). ALCA describes the environmental properties of an existing

system with all its activities associated with the product or service that is generated. All the burdens in connection with the production and use of the product are specified at a specified period. On the other hand, CLCA takes into consideration the possible consequences of the changes occurring in a production system throughout its product's life cycle.

In accordance with the International Organization for Standardization (ISO) 14040 and 14044 standards as described in the International Reference Life Cycle Data System (ILCD) handbook (ILCD 2010), LCA is carried out using four main interdependent phases or methodological frameworks (ISO 2006) namely:

1. Goal and scope definition
2. Life cycle inventory analysis (LCI)
3. Life cycle impact assessment (LCIA)
4. Interpretation

The 'goal and scope' phase is the first step in carrying out LCA study and it comprises five major steps namely:

- Functional unit (FU), which spells out the context of the studies. The FU is the basis of LCA study and it quantitatively measures the product's functions for possible comparisons of the assessed product/process with others (Rebitzer et al. 2004). The FU also provides a reference to which all the inputs and outputs of the system are connected and it must be uniform throughout the LCA study of a particular product. The FU mostly used for biofuels include 'kilometers covered by the bio-fueled vehicle', 'MJ of biofuel produced', 'tonne of biofuel produced', 'kg' of biofuel produced' etc.
- System boundary, which specifies the inclusion or exclusion of certain production processes for the LCA study.
- Assumptions and limitation, which normally depends on the case study under consideration.
- Allocation methods, which helps to divide the environmental damages within the production system especially when products share the same process in the system.
- Impact categories selection where the potential environmental impacts to be studies are carefully chosen based on pre-defined recommendations. Allocation methods used to assign environmental impacts between biofuels and their co-products include mass allocation, energy allocation, market-value allocation and displacement, substitution or system expansion.

In this chapter, LCA studies would consider mass and energy allocation method, which is based on the mass, and energy content of materials and energy resources.

LCI is the phase of the LCA study where all the input and output flow resources are stated with their respective amounts in relation to the functional unit (Suh and Huppes 2005). Materials and energy resources as well as emissions and wastes as outputs are also listed as part of the LCI. Most often, the quantities of emissions are given in the software used for the study. During this stage, a flow model

usually in a form of flow diagram for the production process is constructed showing clearly the system boundary.

LCIA phase is the step where the chosen potential environmental impacts (as part of the goal and scope) are quantified with the aid of software or any assessment medium. Computer aided softwares like SimaPro (System for Integrated environmental Assessment of PROducts which was developed by Pré consultants), Gabi 4 (Ganzheitliche Bilanz, which was developed by PE international), Umberto (which was developed by IFU Hamburg GmbH), Chain Management by Life Cycle Assessment (CMLCA), The Boustead Model 5.0, Ecoscan 3.0, Environmental Priority Strategies (EPS), Global Emission Model for Integrated Systems (GEMIS), LCAPIX, Missing Inventory Estimation (MIE 3.0), REGIS, SPOLD Data Exchange software, Waste-Integrated Systems Assessment for Recovery and Disposal (WISARD) etc. are used for LCA studies. EPS 2000 (Environmental priority strategies) for product development, Cumulative energy demand (CED), ES 1997 (Ecological scarcity), IMPACT 2002, IPCC 2001 for climate change assessment (IPCC 2006) are among the numerous LCIA methods that are implemented in Eco-invent database. LCIA comprises the characterization of the model to be used, classification of the impact categories and impact measurement or quantification.

Throughout this chapter, the potential environmental impacts (based on 11 impact categories) would be assessed according to Eco Indicator 99 (EI 99) and the Agalitarian Approach (AH). Gabi 4 Professional LCI database would be used to generate all the inventory tables for all the studied palm biofuel systems throughout this chapter.

The main impact categories considered in this chapter for palm biofuels LCA studies are human health,¹ ecosystem quality² and resources use³ which are the main considerations under the AH method. Edwards et al. (2007) and Buchholz et al. (2007) have suggested that these impact categories are relevant for assessing the environmental emissions associated with biofuel production systems. Impacts of emissions such as carbon dioxide (CO₂), particulate matter, non-methane hydrocarbons, carbon monoxide (CO), nitrogen oxides (NO_x) etc. are assessed in this chapter.

The final stage of the LCA study is to identify, quantify, evaluate and interpret the results obtained in LCIA. In this stage, the results are summarized and possible recommendations are made in order to improve the system. According to ISO 14040 (2006), the interpretation stage of the LCA study must include the identification of significant environmental impacts considering the results from the LCI,

¹ Human health comprises carcinogens, respiratory organics/inorganics, climate change, ionizing radiation and ozone layer which are measured in disability adjusted life years (DALY) (person-yr).

² Ecosystem quality comprises ecotoxicity, acidification/eutrophication and land use measured in potentially disappeared fraction of species (PDF-m²-yr).

³ Resources use comprises fossil fuel and minerals use which is measured by resource damage (MJ/kg).

evaluation of the study taking into account the sensitivity and accuracy of the data and results and finally drawing conclusion, limitations and recommendations for the study. Optional steps in the LCIA stage include normalization, grouping, and weighting.

During normalization, the results from the LCA study are compared with the total impacts in the system of interest. During grouping, the impact categories are sorted and ranked based on chosen criteria. ‘Weighting’ takes into account the weighing of the impact categories in relation to each other before summing them up to obtain the total environmental impact.

The system boundary of LCA study can take various forms. *Cradle-to-grave* is the full LCA with consideration from raw material extraction (cradle) to product consumption and disposal (grave). *Cradle-to-gate* assesses the product’s life cycle from resource extraction (cradle) to product packaging point (gate) before it is transported to the consumer. Consumption and disposal phases are not considered in cradle-to-gate assessment. *Cradle-to-cradle* is an extreme form of cradle-to-grave assessment where the recycling stage after disposal is considered in the study. This method is actually used to reduce the environmental impacts of the product through sustainable production and consumption. From the recycling stage, a new yet identical product or different products are obtained. *Gate-to-gate* is a partial LCA study that concentrates on only a single stage of a product’s life cycle at a time. For instance, a gate-to-gate LCA of palm biodiesel can be studies with only the production of the oil palm seedlings assessed for potential environmental impacts. A *well-to-wheel* assessment is specifically used for biofuels LCA in which the study considers raw material extraction to the use in vehicles. Within this particular assessment tool, various stages like *well-to-station*, *well-to-tank*, *tank-to-wheel*, *station-to-wheel* and *plug-to-wheel* can be considered.

For commercial scale production of biofuels from oil palm, the net energy requirements for each production subsystem must be critically assessed in order to ensure the efficiencies of the production systems. Oil palm cultivation, palm oil milling and palm biofuels production are quite different with each producing region or system thus the need to carefully assess the inventory. For an efficient LCA study, there must be standardized approaches and practices (Santy 2010).

5.4 Life Cycle Assessment of Biodiesel Production from Oil Palm Biomass

Palm biodiesel can be produced from oil palm biomass such as crude palm oil (CPO), refined, bleached and deodorized palm oil (RBDPO), crude palm kernel oil (CPKO), refined bleached and deodorized palm kernel oil (RBDPKO), palm olein, palm stearin, palm fatty acid distillate (PFAD) and pyrolysed oil from EFB, OPF, PPF, PKS and PKC. The production processes for the various palm biodiesel have been discussed in Chap. 4. The production of FFB is detailed in Chap. 3.

Following the ISO 14040 and 14044, LCA studies for palm biodiesel from different palm biomass are presented independently based on Malaysian oil palm and palm oil production conditions.

5.4.1 LCA Methodology

5.4.1.1 Goal and Scope

The goals of this section are:

- To establish inventory of materials and energy resources associated with the production of palm biodiesel over its entire life cycle using the ‘gate-to-gate’ LCA variant.
- To establish a full chain energy analysis (and energy efficiency) of the various subsystems involved in biodiesel production from liquid oil palm biomass.
- To identify and compare the environmental damages associated with the palm biodiesel production from different liquid oil palm biomass.
- To identify the major unit operations with high environmental loads and suggest possible improvement options.

5.4.1.2 Definition of System Boundary and Functional Unit

The summary of the palm biodiesel system boundary is shown in Fig. 5.1. The nursery produces a single oil palm seedling (0.6–0.8 kg) and transports it to the gate of the plantation.

The plantation subunit produces 1 kg FFB for the oil mill; the palm mills produce 1 kg CPO (from FFB) and 1 kg CPKO (from palm kernel nuts) for the refinery; the refinery processes CPO/CPKO into 1 kg RBDPO and 1 kg RBDPKO as well as PFAD (which is considered waste) for the biodiesel production unit. The biodiesel units⁴ produce and transports 1 kg palm biodiesel to the gate of consumer and finally the consumer combusts 1 kg biodiesel in vehicle’s diesel engine.

For a chosen functional unit of 1 kg product from each subunit of Malaysian palm (CPO, RBDPO, CPKO, RBDPKO, PFAD) biodiesel production system, the gate-to-gate system boundary for the LCA study includes:

- Oil palm nursery in polythene bags (FU = 1 seedling: ~0.69 kg).
- Oil palm production (i.e. production of FFB) (FU = 1 kg FFB).
- Palm oil milling (CPO production) with power from CHP plant (FU = 1 kg CPO).

⁴ ‘Biodiesel production units’ refer to the transesterification stage of the whole palm biodiesel production system.

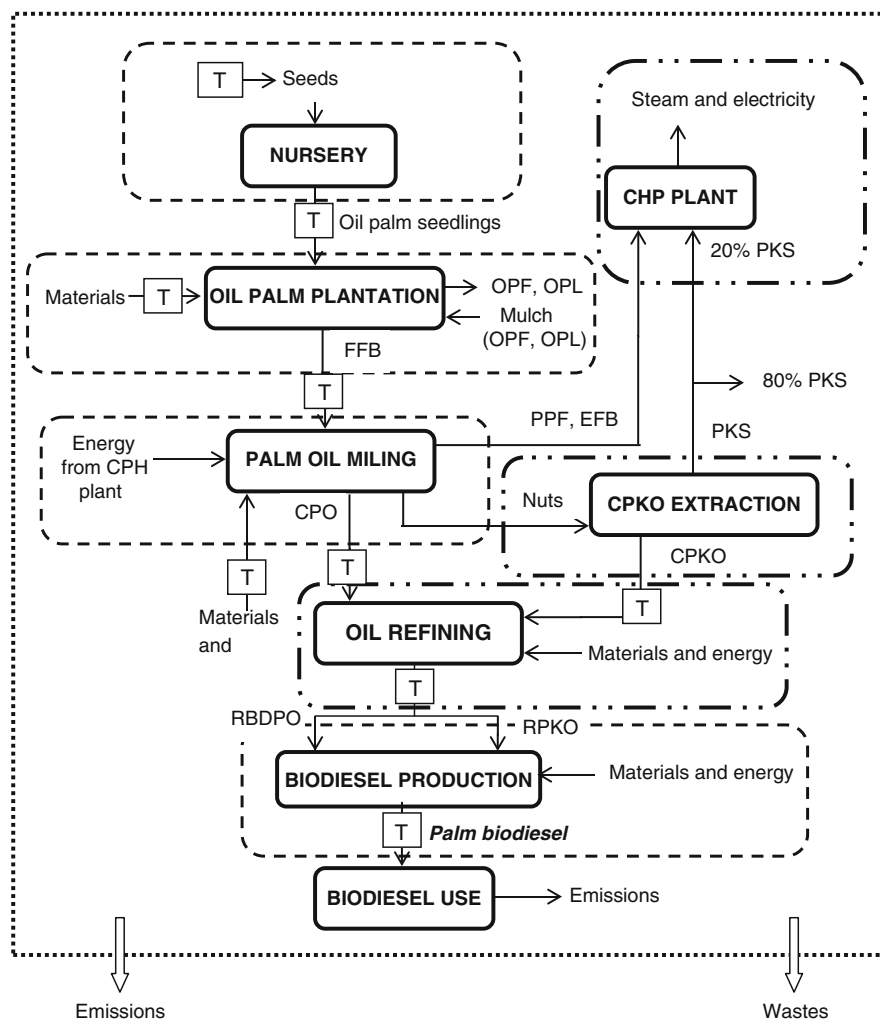


Fig. 5.1 System boundary for LCA study of palm biodiesel production system (CHP plant is considered an isolated system, which supplies energy for utilization in the mill)

- Palm kernel cracking for CPKO with power from CHP plant (FU = 1 kg CPKO).
- CPO and CPKO refining (FU = 1 kg RBDPO, 1 kg RBDPKO).
- Palm biodiesel production (FU = 1 kg palm biodiesel).
- 100 % Palm biodiesel use in diesel engines (FU = 1 kg palm biodiesel).
- CHP generation (FU = 1 kg steam, 1 MJ electricity) from solid palm wastes like PPF and PKS.

The gate-to-gate LCA study starts with the raising of germinated seeds to obtain a single seedling, which is then transported to the gate of the plantation field thus the transportation of materials and other chemicals is part of each subunit. Series of gate-to-gate LCA studies are carried out for each subunit within the biodiesel production system based on the FU defined.

The system boundary however, would not include:

- The production of materials and chemicals as raw materials.
- The production of equipment and machinery, land and buildings for housing the plants.
- The production of energy and utilities (e.g. electricity, fossil fuels etc.) except steam and bio-electricity generation from solid palm wastes. Novizar and Dwi (2010) have reported the negligible energy and environmental contributions from the production of machinery and buildings based on per kilogram inputs due to the negligible amount of energy accounted for when the energy embodied in the machinery is distributed over the amount of outputs from the machine over its entire life cycle.
- The treatment of POME for biogas production but POME is assumed to be used elsewhere for biogas production.
- Disposal of polythene bags (which were used for nursing the palm seeds) was not considered due to lack of data.
- Due to the absence of data on carbon stock, peat oxidation and carbon emissions from peat land for oil palm cultivation, they were not included in this LCA study. Though land use-change and loss of biodiversity has been associated with oil palm cultivation, in Malaysia, oil palm plantations are mainly established on old agricultural land or previously logged-over forest land with progressively sustainable management practices associated with it (see Appendix F).

5.4.2 Life Cycle Inventory Analysis

5.4.2.1 Data Collection

Data used for the LCI analyses were obtained from published literature reviews (Yusoff and Hansen 2007; Schmidt 2007), Ecoinvent database (GaBi 4.0), published experimental and pilot production results (Choo et al. 2011; Novizar and Dwi 2010; Choosak et al. 2009; Subramaniam et al. 2004; Womeni et al. 2010) and estimations based on Malaysia's oil palm industry (MPOB 2010). Data for pesticides and fertilizer emissions during and after application to the nursery and plantation were based on worse case scenarios in which the active ingredients as suggested by Schmidt (2007) were considered equally distributed to air, water and soil. The LCI of all the subsystems of the palm biodiesel production systems are shown in Appendix A.

5.4.2.2 Assumptions and Limitations

For this study, calculations of environmental impacts from plantation subunit of the palm biodiesel system were based on 142 palms/ha and 21 tonnes FFB/year (Yusoff and Hansen 2007; Henson 2005; Yee et al. 2009; Fairhurst and McLaughlin 2009; MPOB 2010) on mineral soils thus no consideration for land clearing. Palm oil plantation in Malaysia is mostly done on mineral soils, peat forest, primary and secondary forests. However, presently, due to lack of land availability and the move towards sustainability, most farmers are resorting to palm cultivation on grassland or degraded land (MPOB 2010; Fairhurst and McLaughlin 2009). The yield of FFB is reduced by $\sim 20\%$ when degraded land or grassland is used for cultivation (MPOB 2010) but can be improved through appropriate sustainable means such as the use of organic fertilizers. About 8.6 tonnes of CPO, 0.25 tonnes of CPKO, 0.50 tonnes of PKC, 0.75 tonnes of PKS, 18 tonnes of OPF, 3 tonnes of OPT, 15 tonnes of EFB and 3 tonnes of PPF are produced from a hectare of oil palm cultivated land annually (Schmidt 2007). OPF, EFB, POME can be utilized as mulching and fertilizing materials which could add more value to the oil palm and help reduce GHG emissions from the use of chemical fertilizers in the plantation. Fertilizers, pesticides and herbicides are assumed to be applied with average amounts for a period of 9 months for nursery and 25 years for plantation. Some inputs and output data throughout the supply chain were difficult to quantify hence were excluded during the energy balance calculations. However, these excluded data had insignificant impact on the environment since their values were relatively insignificant in weight.

About 0.05–0.08 MJ electricity is required to process 1 kg FFB into CPO (Yusoff and Hansen 2007). The CHP plant of the mill is assumed to utilize PPF and PKS as fuels for the generation of steam and electricity to be used by the mill. In this study, an independent environmental impact assessment was carried on the CHP plant for a MJ of bio-electricity to feed the palm mills. Electricity and steam input into the CPO and CPKO production units are considered net-zero emission energy inputs. Biogas and other emissions from POME are assumed to be released into the environment without treatment and gas capture.

In Malaysia presently, almost 99 % of the biodiesel plants use the conventional esterification and transesterification methods (Choo et al. 2011). For the processing of 1 tonne CPO/CPKO, about 150 and 8 kg of methanol and sodium hydroxide are used respectively. Electricity and steam used by the plants are assumed to be sourced from the national grid.

For transportations, the nursery field is assumed to be about 1.7 km away from the oil palm plantation field. The palm oil mill is also assumed to be situated closer to the oil palm plantation. CPO transportation to CPO refinery is assumed to be part of the biodiesel production plant. The polythene bags which were used by the nursery are assumed to be sold for recycling after transplanting of the seedlings.

The method chosen for partitioning of co-products in this study was based on weighted allocation which is found to be consistent with least uncertainties. EFB, PPF, PKC, PKS and PFAD are considered co-products and weight allocations are

assigned accordingly. System expansion was done for OPF, OPL, EFB for nutrient recycle in the palm plantation. All calculations were based on annual oil palm cultivation on a hectare land area. Some co-products like OPF from the subunits are considered utilizable thus included as energy output. System expansion is thus considered for EFB, PPF, POME and PKS for the production of biofuels to supplement the mills.

5.4.3 Energy Balance for Palm Biodiesel Production System

Energy balance is one of the important ways of assessing the energy efficiency and sustainability of a production system like biodiesel production from oil palm biomass. There are two types of energy used during the whole production chain for palm biodiesel production namely direct and indirect energy. Direct energy is the energy possessed by diesel, steam, electricity which are used during processing. Indirect energy is the energy possessed by the material resources as inputs or outputs of the production system. The energy balance is carried out by the difference between the sum of the resulting or output energy (products and co-products) and the sum of the entering energy into the system. These values therefore make up the total energy efficiency (comprising the net energy value (NEV) and net energy ratio (NER). The overall output energy must outweigh that for input resources for a system to be energy efficient.

Figure 5.2 shows the energy efficiencies (NER and NEV) for each subsystem in the palm biodiesel production system. The oil palm nursery is the first stage in cultivating the oil palm biomass (FFB) for biodiesel production. The nursery is established in order to ensure high early yield of FFB as well as to reduce the period of immaturity of palm tree on the plantation land. The nursery receives about 4.0–10.0 g of fertilizers (in the form of N–P–K) and about 1.5–2.0 g of pesticides and herbicides until transplanting. Water consumption in the nursery of a single oil palm seedling is about 2.0–3.0 l, which is applied manually. The polythene bags, fertilizers, pesticides and herbicides are transported over a distance of 0.5–1.5 km to the plantation site. Appendix A, Table A.1 shows the resource inputs and outputs into the production of a single oil palm seedling for FFB and subsequent palm biodiesel production. The energy inputs and outputs into the production of a single palm seedling are ~27 and ~81 MJ/kg (including emissions) of a seedling respectively. However, with allocations to co-products and omission to emissions, the nursery recorded a total energy output of ~25 MJ/kg of a seedling. Based on this, the NER and NEV were 0.946 and –1.432 MJ (Fig. 5.2). The negative NEV signifies unfavourable results (energy of inputs outweighs that for the outputs) which resulted from the heavy use of polythene bags, fertilizers, pesticides and herbicides. Pesticides and herbicides formed more than 90 % of the total resource inputs (excluding the energy from germinated seeds) in the nursery, which was comparatively higher than their use in the plantation.

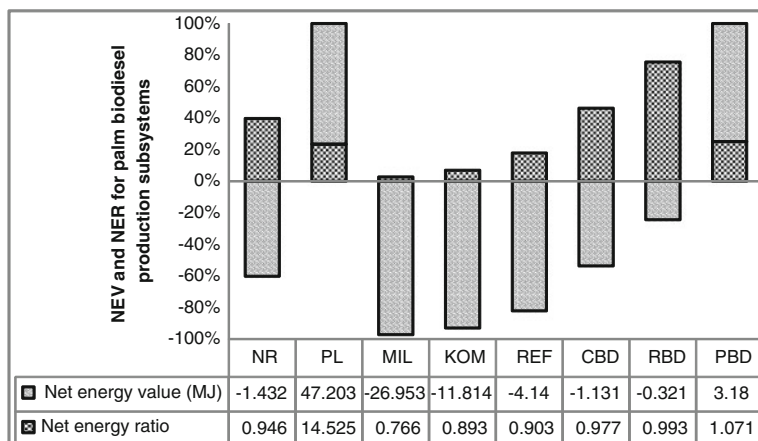


Fig. 5.2 Net energy efficiencies for palm oil biodiesel production sub-systems. (NR Nursery (1 seedling); PL: Plantation (1 kg FFB); MIL: Oil milling (1 kg CPO); KOM: Kernel oil milling (1 kg CPKO); REF: Oil refining (1 kg CPO/CPKO); CBD: CPO/CPKO Biodiesel production (1 kg); RBD: RBDPO/RBDPKO Biodiesel production (1 kg); PBD: PFAD Biodiesel production (1 kg))

Reduction in these high energy input resources and their replacement with organic fertilizers and low energy value materials may result in better NEV.

Renewability (i.e. the ratio of net energy outputs to the net fossil energy inputs) of the nursery system was also 8.142, which indicates a net energy gain (ratio more than 1) and reduction in fossil fuel use during the nursery of a single palm seedling. The main input data into the cultivation of 1 kg FFB were the materials and energy resources whilst the outputs also include the emissions to air, water and soil as well as the major products and co-products. Chapter 3, Sect. 3.3 discusses into details the main activities involved in oil palm cultivation.

Fertilizers and pesticides (including herbicides) are major materials that are consumed by the oil palm plantation with total consumption rate of 0.0518 and 0.00141 kg respectively for 1 kg FFB. The amount of applied fertilizers and pesticides are shown in Appendix A, Table A.2. Plantation establishment, maintenance and harvesting are carried out manually whilst transportation of the machinery, tracks etc. also involve the use of petroleum diesel fuel. Literature data (Schmidt 2007; Zulkifli et al. 2010; Yusoff and Hansen 2007) for the consumption of materials and energy for the oil palm plantation were used for this LCA study. The net input energy for the plantation stage (including transportation of FFB to mill) was estimated at about 3.49 MJ/kg which is closer to that for soybean production (2.52 MJ/kg) without transportation (Pimentel and Patzek 2005). The NEV and NER for FFB production were found to be higher positive values at 47.203 and 14.525 MJ respectively compared to the energy balance for the other subsystems in this study. In comparison with soybean production, Donato et al. (2005) reports NEV and NER values of 12.68 and 1.57 MJ respectively, which are quite lower than those reported

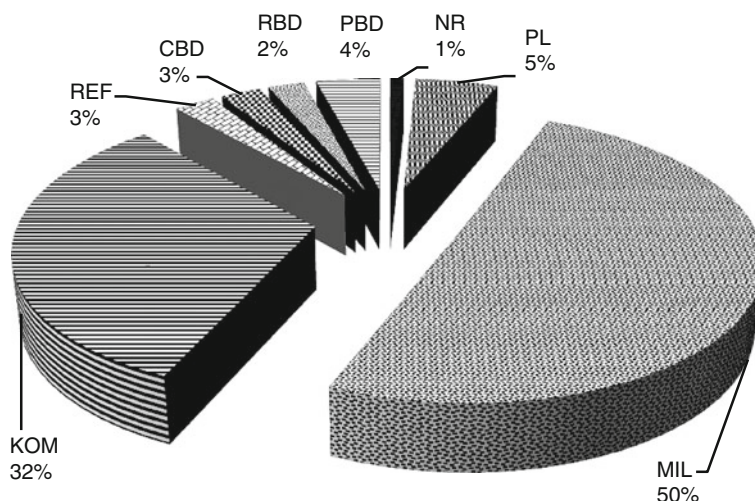


Fig. 5.3 Renewability of the subunits within the palm biodiesel production system. (*NR* Nursery (1 seedling); *PL*: Plantation (1 kg FFB); *MIL*: Oil milling (1 kg CPO); *KOM*: Kernel oil milling (1 kg CPKO); *REF*: Oil refining (1 kg CPO/CPKO); *CBD*: CPO/CPKO Biodiesel production (1 kg); *RBD*: RBDPO/RBDPKO Biodiesel production (1 kg); *PBD*: PFAD Biodiesel production (1 kg))

for oil palm in this study. Based on the *NER* value for 1 kg FFB production, which is greater than unity, it can be inferred that oil palm cultivation is a net energy generator. This study reports similar results from Corley and Tinker (2003) who concluded that oil palm is regarded as a net source of useful energy due to its energy efficiency, which is more than unity. Renewability of the plantation subsystem was estimated at 49.23, which is better than all the other subunits except the milling of CPO and CPKO. Figure 5.3 shows the renewability of the individual production subunits within the palm biodiesel system.

Apart from the unit for PFAD biodiesel and FFB production, all the other subunits recorded negative *NEV*. Though these values are not high, they are considered unhealthy for environmental sustainability because the production systems may contribute to high emissions into the environment endangering lives on the ecosystem. The CPO milling stage had the worst scenario where both the *NEV* and *NER* were lower compared to the other stages (Fig. 5.2). These negative values shows that high amounts of energy and materials (with high energy contents) were consumed during the production of 1 kg CPO production (see Appendix A, Table A.3). In the mill, it was assumed that bio-electricity and steam from the CHP plant were utilized for FFB processing.

Though the *NEV* and *NER* are negative, the renewability of the CPO milling was the best and highly encouraging at about 466.53 (Fig. 5.3) since only a negligible amount of fossil diesel was used by the mill. This will eventually reduce the overall emissions contributed by the mill.

The palm kernel milling recorded better energy efficiencies compared to the CPO milling process due to the high energy content of the co-products from the CPKO milling stage (see Appendix A, Table A.4). Appendix A, Table A.5 summarizes the resource inputs and outputs into the refinery unit of the palm biodiesel system for 1 kg RBDPO/RBDPKO. The nursery recorded the lowest renewability value due to the small energy content of output product transported over some distance to the plantation site. For instance, the amount of diesel fuel used to transport 1000 kg of materials over 1 km distance would be the same when 1 kg of materials is transported over that same distance. This means that, on large scale production, renewability for the nursery might increase as the same amount of petroleum diesel would be used to transport huge amount of seedlings to the plantation sites. This is same for all the units when they are scaled-up for commercial production. In order to improve upon the renewability of the subsystems for palm biodiesel production, they must be sited closer to each other especially the CHP plant in order to easily and economically draw bio-energy for sustainable production of palm biodiesel. This can also reduce the amount of fossil fuel used for transportation within and outside the plants.

PFAD biodiesel production unit recorded positive NER and NEV of 1.071 and 3.18 MJ respectively (see Appendix A, Table A.8) compared to the others. This is mainly due to the low energy value of PFAD (36.01 MJ/kg) which was converted to a high-energy value PFAD biodiesel (39.84 MJ/kg). The feedstocks, RBDPO and CPO, had comparatively higher energy values of 37.60 and 39.40 MJ respectively (see Appendix A, Table A.6 and Appendix A, Table A.7 for LCI of RBDPO and CPO respectively) compared to their biodiesels' energy values, which eventually reduced their energy efficiencies. However, Pimentel and Patzek (2005) have also reported a NER value of 0.79 for soybean oil biodiesel which is lower compared to all the biodiesels (from PFAD, CPO and RBDPO) production units in this study hence can be concluded according to the conditions outlined in this study that palm biodiesel is environmentally sustainable (via LCA) compared to soybean oil biodiesel.

Energy, which included petroleum diesel fuel, electricity (from either CHP plant or grid) and steam, was the most consumed resources by all the subunits followed by chemical use (like polyethene bags, methanol, bleaching earth, phosphoric and sulphuric acid, sodium hydroxide etc.). Figure 5.4 summarizes the energy contributions of resource inputs into the sub-production units within the palm biodiesel production system. Palm oil mills (CPO and CPKO mills) consumed the most energy (99.6 and 99.5 % of the total energy inputs respectively) with the plantation consuming the least energy (4.1 % of total energy input into plantation) (Fig. 5.4).

However, the energy utilized by the mills is produced by the CHP plant within the mills, which is sufficient for the mills (Husain et al. 2003). In order of environmental benefits with respect to energy efficiency, the pattern: 1 kg FFB production > 1 kg PFAD biodiesel production > 1 kg RBDPO biodiesel production > 1 kg CPO/CPKO biodiesel production > 1 oil palm seedling

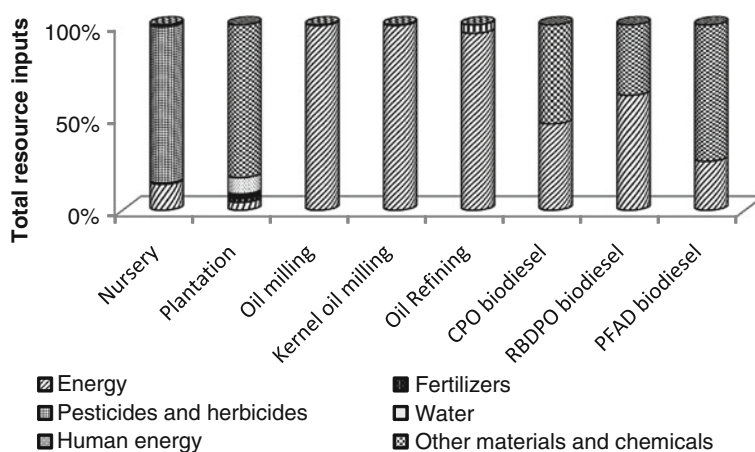


Fig. 5.4 Energy contributions of resource inputs into the various sub-units of the palm biodiesel production system. 'Other materials and chemicals' refer to bleaching earth, sodium hydroxide, sulphuric acid, phosphoric acid, methanol, polyethene bags, organic mulch and fertilizers from OPF, OPL etc

production >1 kg RBDPO production >1 kg CPKO production >1 kg CPO production is followed according to this study.

5.4.4 LCA Results and Interpretation for Palm Biodiesel Production

Figure 5.5 shows the total environmental impacts associated with the production of palm biodiesel throughout its life cycle with respect to 1 kg FU for each subunit.

Of all the production sub-units, the raising of a single oil palm seedling contributed the most amount of carcinogens (83 %), ionizing radiation (76 %), ozone layer depletion (68 %), climate change (54 %), minerals (83 %) acidification and eutrophication (90 %) with respect to the total potential impact categories from the other subunits. However, acidification/eutrophication was the highest potential impact category from the nursery with about 96 % of the total acidification/eutrophication potentials from all the subunits. This high emissions resulting in these impacts are due to the heavy use of fertilizers (ecotoxicity, acidification/eutrophication and radiation), pesticides and herbicides (radiation, ecotoxicity, carcinogens etc.) as well as polyethene bags (ozone layer depletion etc.) used for raising seedlings. Paraquat dichloride, which is a type of high-energy value-fertilizer commonly used by the nursery and plantation, is found to also emit substantial amounts of minerals and metals into the soil eventually contributing to high negative environmental impacts. The use of slurry from anaerobic digestion of POME as organic

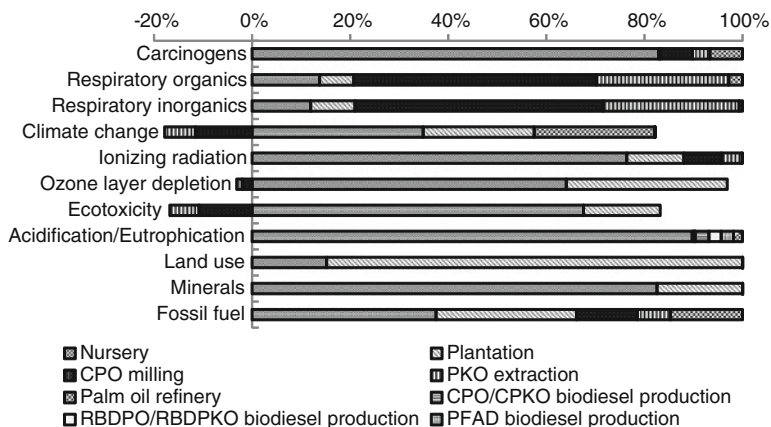


Fig. 5.5 Total environmental impact potentials for palm biodiesel production sub-units per functional unit chosen for the individual subsystems

fertilizer as well as other sustainable ways of eliminating pests and herbs in the nursery (Sect. 4.2) can help minimize these environmental impacts.

For the production of 1 kg FFB, five of the studied impact categories were significant. Respiratory inorganics, climate change, acidification/eutrophication, ecotoxicity and fossil fuel contributed about 61, 15, 10, 1 and 11 % respectively. In comparison with the other subunits, land use contributed the highest (about 85 %) of the total land used by all the subunits but the impacts from land use in the plantation were insignificant. The use of fertilizers, pesticides, herbicides and fossil fuels were the main contributing emissions to these potential impacts and the reduction in their use or their replacement with organic ones like POME, would reduce these impacts drastically. Figure 5.6 shows the overall contribution of each subunit to the environmental impact categories.

The production of 1 kg FFB for palm biodiesel contributed overall impact of about 2 % of the total emissions from the life cycle of palm biodiesel (Fig. 5.6). Choo et al. (2011) have also reported that for a production of 1 tonne FFB, a total amount of 119 kg CO₂ eq. GHG is emitted from the system. From their studies, fertilizer use contributed the highest GHG emissions of about 48.7 %. Again, for a cradle-to-grave LCA study by Hassan et al. (2011), the emissions of GHGs from the production of 1 MJ palm biodiesel (from CPO) was 56 g CO₂-eq per MJ biodiesel with about 43 % accounting for FFB production (about 24 g CO₂-eq per MJ). The reasons for the high values from these studies are that they considered POME and other co-products as wastes without further utilization hence high amounts of emission contributions.

For the production of 1 kg CPO, about 99 % of the total emissions from the subunit came from respiratory inorganics. Acidification/eutrophication was the next contributing impact category (about 1.6 % of the total impacts) with the nine others being insignificant. However, comparing with the other subunits, climate

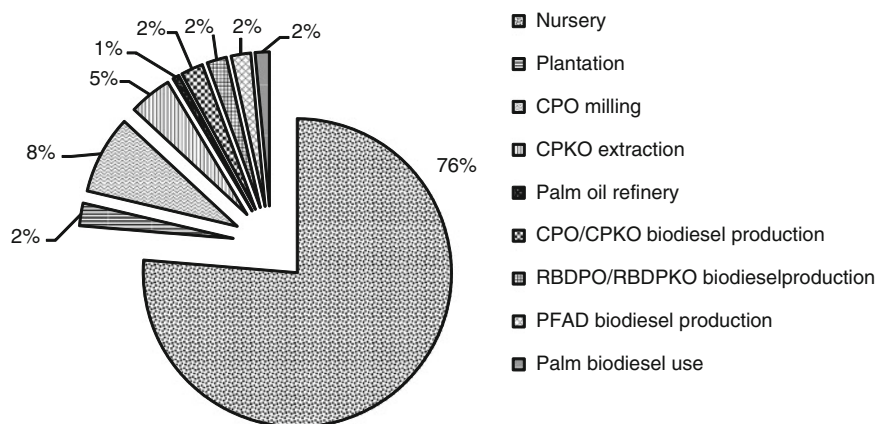


Fig. 5.6 Total environmental impacts associated with the production of palm biodiesel (1 kg FU gate-to-gate LCA)

change, respiratory organics/inorganics, ecotoxicity and fossil fuel impact categories contributed significantly high impacts (Fig. 5.5). These emissions mostly came from the initial discharge of POME before treatment and biogas capture as well as the petroleum diesel used to drive the screw presses. Overall, the CPO milling stage contributed about 8 % of the total emissions from the life cycle of palm biodiesel (Fig. 5.6). In the palm oil mill, when POME is treated for biogas capture, about 21.2 g CO₂-eq. for every MJ of palm biodiesel is emitted from the mill as against about 33.2 g CO₂ eq. per MJ system without biogas capture (Choo et al. 2011).

For the production of 1 kg CPKO for biodiesel production, the dominant potential impact categories were respiratory inorganics (~97 %), acidification and eutrophication (~1.6 %), fossil fuel (~1.4 %) and carcinogens (~0.2 %). These emissions came from the initial emissions from the untreated waste-water and use of diesel fuels for palm nut cracking and pressing therefore the minimization of diesel use (replacing with biodiesel) and the treatment of wastes would reduce these impacts. However, the climate change potential was insignificant due to the use of bioenergy from the CHP plant during CPKO production. The small share from this category resulted from the emissions from the transportation fuel (diesel fuel). Generally, the treatment of POME and all wastes streams from the mills for biogas capture and use may result in significant decrease in acidification/eutrophication potentials as well as respiratory inorganics. For all the subunits within the biodiesel production system, CPKO production contributed about 5 % of the total environmental impacts throughout the life cycle of palm biodiesel (Fig. 5.6).

The main wastes generated in the palm oil milling units with high environmental impacts are POME and PKC. The impact categories contributed by these wastes are respiratory organics and climate change. For this study, POME is assumed to be discharged into its treatment plant for biogas capture in order to

reduce air emissions in the palm biofuel industry and save the environment. PKC is also sent to the palm bioethanol production plant for conversion into bioethanol.

Out of the 11 impact categories studied, the subunit for the refining of CPO/CPKO into 1 kg RBDPO/RBDPKO had five potential impact categories contributing significantly (Fig. 5.5). Climate change was the highest impact category with about 58 % of the total impacts. Fossil fuel, respiratory inorganics, acidification/eutrophication and carcinogens contributed about 19.6, 16.3, 3.9 and 1.9 % respectively. These contributions came mainly from the use of petroleum diesel fuel emitting CO, CO₂, N₂O, respiratory gases etc. The overall impact contribution from the refinery was about 1 % compared to the other subunits (Fig. 5.6).

The production of 1 kg palm biodiesel from CPO/CPKO, RBDPO/RBDPKO and PFAD contributed almost the same amount of emissions with acidification/eutrophication potential being the highest impact category. In the CPO/CPKO biodiesel production unit, acidification/eutrophication contributed about 99.8 % of the total impacts of that unit whilst in the RBDPO/RBDPKO biodiesel production and PFAD biodiesel production units, 99.9 and 99.7 % of the total impacts respectively from each unit resulted from acidification and eutrophication. The climate change potentials for CPO/CPKO biodiesel, RBDPO/RBDPKO biodiesel and PFAD biodiesel production units were insignificant at 1.73E-09 PDF·m²·yr, 1.54E-09 PDF·m²·yr and 1.55E-09 PDF·m²·yr respectively. There were insignificant emissions contributions from ozone layer depletion, ecotoxicity and ionizing irradiation. In all, each of the three subunits contributed 2 % of the total impacts from all the subunits from nursery establishment to biodiesel production.

The life cycle inventory for the combustion of biodiesel is shown in Appendix A, Table A.9. The combustion of 100 % palm biodiesel in diesel engines showed insignificant impacts in all the categories apart from acidification/eutrophication potential which was significant though very small (about 2.508E-03 PDF·m²·yr). Methanol used for transesterification is sourced from fossil fuel hence the palm biodiesel produced contains fossil carbon. For every tonne of palm biodiesel combusted, about 760 kg of CO₂-eq. is emitted into the environment (Lin et al. 2008). However, Vanichseni et al. (2002) has reported that based on average Malaysia's palm biodiesel fossil carbon content, about 5.9 % of CO₂-eq. is emitted as opposed to Lin et al. (2008). There are differences between the CO₂ eq. emitted from palm biodiesel production and combustion from various researches due to allocation methods, energy contents of inputs and output materials as well as carbon credits associated with co-products. Figure 5.7 shows the impacts of palm biodiesel production subsystems on ecosystem quality, Human health and resource use.

Ecosystem depletion (land use, acidification/eutrophication and ecotoxicity potentials) was the highest environmental impact potential and the nursery as well as the three types of palm biodiesel production subunits of the whole palm biodiesel production system were the main contributors. Human health (carcinogens, respiratory organics/inorganics, ionizing radiation, climate change and ozone layer depletion) was also highly affected by emissions from the plantation, CPO milling, CPKO extraction and refining subunits whilst resource use impact was high in the plantation and oil refinery.

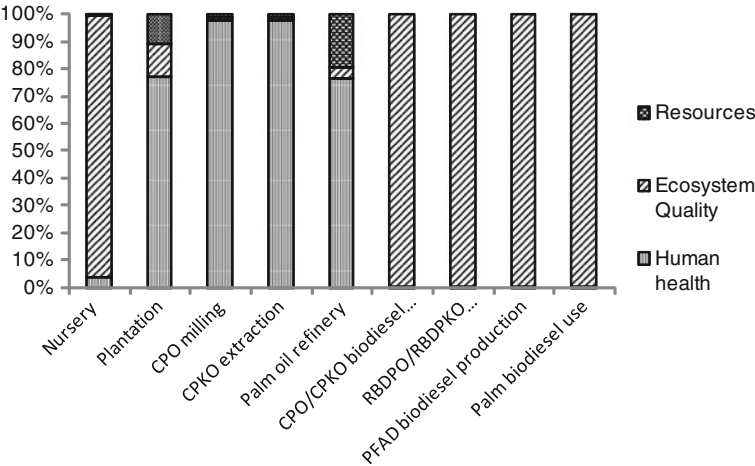


Fig. 5.7 Impacts of palm biodiesel production on ecosystem quality, human health and resource use

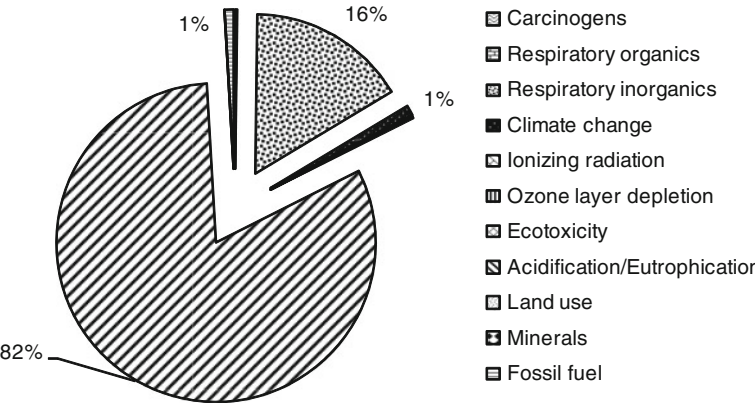


Fig. 5.8 Total environmental contributions of impact categories associated with all the production subunits within the palm biodiesel production system (1 kg FU gate-to-gate LCA)

Figure 5.8 shows the contributions of each of the 11 impact categories on the environmental sustainability of palm biodiesel production. In sum, for the production of a kg feedstock at each subunit for palm biodiesel production, acidification/eutrophication potential was the most significant impact claiming about 82 % of the total impacts. Respiratory inorganics, climate change and fossil fuel use were the other significant categories with 16, 1 and 1 % respectively. Plantation and nursery were the main contributors to acidification and eutrophication potential whilst particulate matter emissions from fossil fuel use also contributed significantly to increase in respiratory inorganics, climate change and fossil fuel

use potentials. When POME and other co-products from the plantation and milling units are not utilized, the potential impact categories recorded in this study would have been highly significant.

As the RSPO works hard to ensure sustainable oil palm and palm oil production, waste management would help the palm oil industry to obtain emission credits from the grid when POME, EFB, PPF, OPT etc. are utilized for bioenergy and bio-fertilizers. If all the oil palm wastes from Malaysia's palm oil industry are assumed to be utilized for bioenergy and biofuels, a potential energy generation of about 100 TWh/yr (about 75 % of the total electricity generation in 2010) would be produced for sustainable development (Economic Planning Unit 2006).

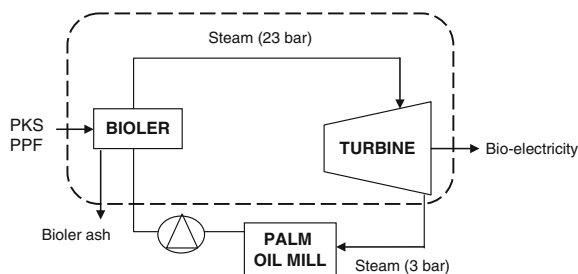
5.5 LCA of Combined Heat and Power Generation Plant in Palm Oil Mills

5.5.1 System Boundary, Functional Unit and LCI

The aim of this section is to carry out LCA study for the production of bio-electricity and steam from oil palm biomass (specifically PKS and PPF) for use in palm oil mills based on Malaysian conditions. From Fig. 5.1, the CHP plant can be expanded (see Fig. 5.9) to define clearly the system boundary for palm biomass cogeneration. Literature data from Hassan et al. (2011) were used for the inventory assessment for this study. In most CHP plants in the world, fossil fuel is used to fire the boilers whereby the fuel is fed under pressure through a pipe to the burner to be ignited by an electric ignition system. Almost all the CHP plants in Malaysia utilizes fossil fuel for start-ups of the boiler and according to Subramaniam et al. (2008), about 0.37 liters of petroleum diesel is needed to fire the palm solid biomass generated after processing a tonne of FFB.

For a tonne of palm biomass fired for heat production, about 15–17 kg of boiler ash is produced which can be used as concrete materials in building, adsorbents or organic fertilizer in the plantation. After processing of 1 tonne FFB for CPO production, about 104 MJ of electricity could be produced from the PKS, EFB and PPF generated as wastes. However, the amount of electricity needed by a mill to

Fig. 5.9 System boundary for cogeneration of palm biomass



process a tonne of FFB is only about 50–80 MJ (Yusoff and Hansen 2007). In Malaysia, almost all the CHP plants utilize PPF and PKS for power generation. However, EFB (which has high moisture content) is gradually becoming an additional biomass for cogeneration. Because the mill is situated just closer to the CHP plant, transportation using petroleum diesel fuel is also negligible. For this LCA study, a functional unit of 1 MJ electricity is chosen.

5.5.2 LCA of CHP Generation: Results and Interpretation

Water, PPF and PKS were the main material inputs into the CHP plant. For 1 MJ of electricity generated, the total amount of input energy resources was about 36.165 MJ which was higher than the energy output (excluding emissions) (see Appendix B, Table B.1). The estimated NER and NEV for palm biomass cogeneration plant was 0.66 and –12.25 MJ respectively. These values show a negative energy gain for CHP plant thus the need for improvement in energy utilization and pollution control.

Though biomass cogeneration is said to be carbon neutral, there are significant amount of particulate matter and volatile organic compounds (VOC) that are emitted from the process. These substances are even higher when no pollution control equipment like multi-clone, electrostatic precipitator etc. is used. According to this study, the main contributing impact categories in the CHP plant are climate change, fossil fuel use, respiratory inorganics, acidification/eutrophication, ecotoxicity and carcinogen potentials. Due to the emissions of CO₂ and CO from biomass and fossil fuel combustion, climate change potential contributed the highest impact with about 70 % of the total impacts. Fossil fuel and respiratory inorganics potentials recorded about 28 and 2 % of the total impacts from the CHP plant. Direct firing of palm biomass in boilers may lead to significant emissions of particulate matter into the environment when no pollution control measures are taken. The environmental impacts from climate change potential could be reduced by pelletizing or pretreating the biomass before firing in boilers. In this study, pretreatment was not considered hence the emission of soot or black smoke from the plant could contribute to climate change, carcinogens and respiratory organics/inorganics potentials. The technology of CO₂ capture from combustion chimneys is presently under research and development and it would be a better option for sustainable cogeneration of palm biomass into bio-energy.

Another potential impact of ecotoxicity, minerals and respiratory organics came from the boiler ash, which consists of clinkers, and ash. Again, the boiler ash contains traces of metals like aluminium, magnesium, iron etc. which could leach into the soil (if not handled well) resulting in high potentials of acidification/eutrophication and minerals impacts.

5.6 Life Cycle Assessment of Palm Bioethanol Production

Most LCA studies on bioethanol production has been focused on first generation feedstocks (Wang et al. 2007; Feng et al. 2008) which are currently under debate due to their competition with food crops for land. However, few LCA studies have been carried out on second-generation feedstock (like sugarcane bagasse, corn stover, switch grass etc.) conversion into bioethanol as transport fuels (Wang et al. 2011; Luo et al. 2009; Spatari et al. 2005, 2010; Wu et al. 2006). This section studies the LCA of bioethanol production from OPF.

5.6.1 System Boundary, Functional Unit and LCI

The goal of this section's study is to evaluate the environmental impacts associated with the production of palm bioethanol from OPF based on a gate-to-gate LCA approach. The identification of the most environmentally damaging stage of the whole life cycle of palm bioethanol is a major goal. A functional unit of 1 kg palm bioethanol (~ 99.5 wt% bioethanol) is chosen for this study. Palm bioethanol can be produced from lignocellulosic palm residues (second-generation palm feedstocks) like EFB, OPF, OPT, PPF and PKC. However, OPF was chosen as a case study in this chapter because it is the most abundant solid palm biomass. Though there are few cellulosic ethanol production plants on commercial scale in the world presently, intensive research and development on appropriate technologies for producing cellulosic ethanol from palm wastes for instance, could help minimize environmental impacts and head the oil palm industry towards sustainable development. The production processes involved in lignocellulose conversion into bioethanol are discussed in (Chap. 2, Sect. 2.3.2.1). However, the system boundary defined in this LCA study is summarized in Fig. 5.10. A functional unit of 1 kg palm biodiesel is chosen for the study.

The solid residues used as feedstocks are considered wastes from the oil palm plantation hence their production stages in this LCA study are not taken into consideration. The production chain for all the input resources were not considered but their emissions were given by Gabi 4 software. The gate-to-gate LCA for palm nursery to the production of these wastes are elaborated in the previous sections in this chapter (Sect. 5.4). The main subsystems considered for this LCA study are OPF production, bioethanol production and bioethanol use in vehicles. Environmental impacts associated with the use of palm bioethanol are also assessed in this section. The necessary transportations, conversion of the OPF to bioethanol and all associated emissions throughout the product's life cycle are investigated in this LCA study.

Data were collected from published research articles on bioethanol production from OPFs and other types of palm cellulosic ethanol production (Aden et al. 2002; Hong et al. 2012; Goh et al. 2010; Jung et al. 2012). Data gaps or unavailable general data were filled by making some assumptions as stated in this

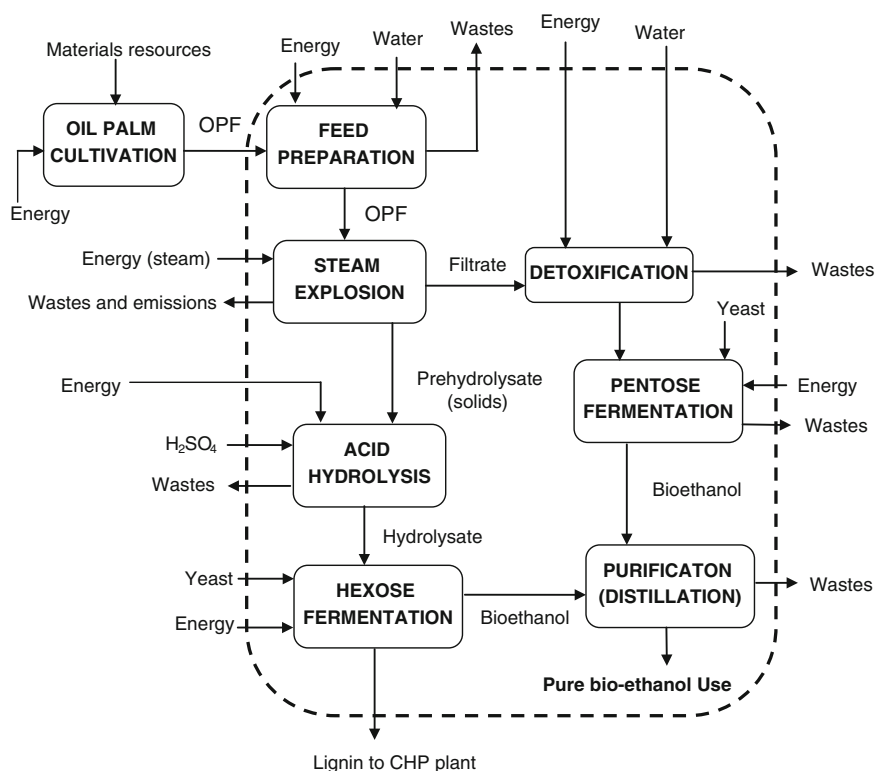


Fig. 5.10 System boundary for LCA study of palm bioethanol production

section. Material and energy balance calculations were carried out on each subunit of the whole bioethanol production system. Appendix C, Table C.1 shows the inventory data for bioethanol production from OPFs.

The first step in the conversion of lignocellulosic materials like solid palm biomass into bioethanol is the pretreatment stage, which comprises cleaning, size reduction, drying and lignin and other extractives removal. This stage is the most energy intensive of the cellulosic bioethanol production system. Lignin and other extractives are removed from the fiber matrix in order to ensure efficient activity of enzymes or acid catalysts on the substrate for high sugar yield. Hydrolysis or saccharification of hemicellulose and cellulose of the OPF are done to release the C5-sugars (pentose) and C6-sugars (hexose) for efficient fermentation. Process configurations like separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), simultaneous saccharification and co-fermentation (SSCF) etc. can be used for bioethanol production. SSF and SSCF are found to produce high yields of bioethanol yet require less energy input compared to SHF. However, these advanced technologies are still under research and development and the LCA study may result in uncertainties due to no means of

validation using commercial processes (Spatari et al. 2010). Enzymes and fungus used during hydrolysis and fermentation of OPF into bioethanol are highly costly though the processes result in high yields compared to when acid catalysts are used. One other energy intensive stage of the conversion process is the bioethanol purification stage, which comprises distillation and dehydration.

Presently, bioethanol used as transportation fuel is mostly blended with gasoline thus tail pipe emissions from the combustion of the blended fuel is vital to assess. However, 100 % bioethanol is more beneficial for good environmental performance hence the environmental impacts from the combustion of 100 % OPF bioethanol are assessed in this study.

OPF contains about 10.26 wt% moisture, 30.19 wt% cellulose, 24.26 wt% hemicellulose, 12.96 wt% lignin, 11.36 wt% ash content, 40.56 wt% glucose, 17.40 wt% xylose, 5.12 wt% water extractives, 5.84 %, ethanol extractives (Goh et al. 2010). A conversion efficiency of 0.877 tonne of bioethanol per tonne of dried OPF is assumed in this study based on the holocellulose content of OPF. Hydrolysis, fermentation and purification (distillation) process efficiencies are assumed to be 90, 95 and 97 % respectively. Separate hydrolysis and fermentation of OPF is used for the bioethanol production in this study. Lignin as a by-product from the conversion process would be used as feed for the boiler in the CHP plant within the oil palm mill.

5.6.2 Palm Bioethanol Production: LCIA Results and Interpretation

The total energy of inputs into the palm bioethanol production unit was higher than the total energy content of the major products (Appendix C, Table C.1). Lignin and fiber extracts were assumed to be utilized by the CHP plant for bio-electricity production. The waste-water from the pretreatment unit carried high energy content (2326.89 MJ) due to the presence of acids, protein, traces of oils and bioactive substances like phenolic compounds in the OPF. If the wastewater is treated and all value-added bio-products are isolated for various purposes, the NER and NEV of the palm bioethanol production system would be positive at 2280.32 and 28.27 MJ respectively. However, in this study, the wastes were considered as by-products without any utilization hence NER of 0.44 and NEV of -46.56 MJ made the whole system energy inefficient. Emissions from the wastes are also high contributing to high environmental impacts. However, the renewability of the system is very high with net renewable energy value (NRnEV) at 37.06 MJ. Yu and Tao (2009) found the NER of bioethanol from cassava to be 0.70 for a MJ of bioethanol produced and this value is far lower than the results from this study in terms of 1 kg bioethanol. Spatari et al. (2005) have also concluded that LCA GHG emissions from switch grass bioethanol are about 57 % lower than those for gasoline.

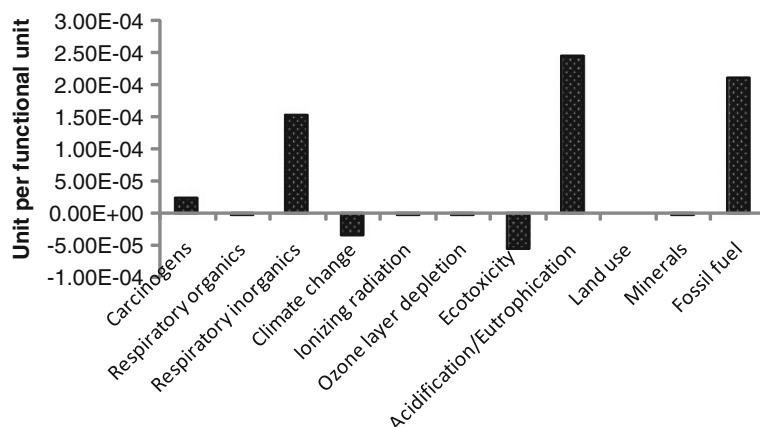


Fig. 5.11 Contributions of environmental impacts from the 11 impact categories for palm bioethanol production. Carcinogens, respiratory organics/inorganics, climate change, ionizing radiation and ozone layer are measured in (DALY) (person.yr); Ecotoxicity, acidification/eutrophication and land use are measured in (PDF·m²·yr); Fossil fuel and minerals use are measured in MJ/kg

Five out of the eleven impact categories studies in this LCA were significant for palm bioethanol production. Figure 5.11 shows the contributions of the impact categories from palm bioethanol production.

Acidification/eutrophication was the highest recorded potential impact with about 45 % of the total impacts followed by climate change potential. Though climate change impact is the highest in this study, the value is highly insignificant compared to that for gasoline and its can be seen that about 80 % reduction of climate change impacts can be achieved with the use of palm bioethanol. Wastewater discharge from the pretreatment stage as well as the emissions from the chemicals used for hydrolysis and fermentation resulted in the high impact from acidification/eutrophication. The use of diesel fuel and electricity from the grid also contributed emissions resulting in climate change impact. Impact potentials from respiratory inorganics (28 %) and fossil fuel use (39 %) were the next highly significant categories but the contributions from minerals, carcinogens, ozone layer depletion and ionizing radiation were hardly noticeable.

Figure 5.12 shows the total impacts from all the 11 impact categories contributed by the individual unit operations within the palm bioethanol production system. The purification stage utilizes a lot of electrical energy from the grid hence its greater contribution (21.4 %) to the overall impacts. The hydrolysis stage also contributed high impacts due to emissions from the use of chemicals like lime, phosphoric acid etc.

According to a report by Choudhary (2012), if cellulosic ethanol is used to replace gasoline on our roads, about 55 g CO₂ eq. per MJ energy could be saved. Overall, resource use carried the greatest impact of 2.11E-04 MJ/kg (about 39 %) contributed by fossil fuel and minerals potentials. Ecosystem depletion and human

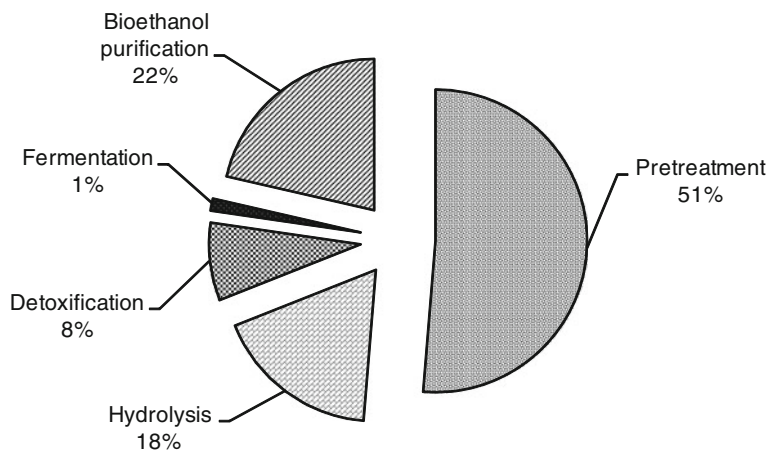


Fig. 5.12 Total environmental impacts from palm bioethanol production subunits

health were also $1.89\text{E-}04 \text{ PDF}\cdot\text{m}^2\cdot\text{yr}$ (about 35 %) and $1.44\text{E-}04 \text{ DALY}$ (about 26 %) respectively. Ecotoxicity/eutrophication (from wastewater and other chemicals) was the major cause of this effect hence the treatment of all wastes or isolation of value added bio-products from the wastes could reduce these impacts.

Switch grass bioethanol (E85) has been assessed on LCA basis that during its combustion, about 57 % GHG emissions reduction could be reached compared to gasoline (Spatari et al. 2005). Their results were closer to those of Wu et al. (2006) who reported GHG emissions reduction of 60–62 % compared to gasoline. Comparing these results with those for OPF bioethanol (E100), about 35–42 % emissions reduction (including GHGs) could be achieved compared to gasoline. First generation bioethanol from corn is found to reduce GHG emissions by 20 % during combustion in vehicles (Feng et al. 2008). Bioethanol from corn in the USA is assessed by Kim and Dale (2008) to save about 0.22–1.06 kg $\text{CO}_2\text{eq.}$ per kg bioethanol (20–36 % GHG emissions savings) when it is combusted.

5.7 LCA of Simultaneous Production of Bio-syngas and Bio-methanol from EFB

5.7.1 Goal, System Boundary and LCI

Malaysia is endowed with over 53 million tonnes of palm biomass which are highly suitable as feedstock for the production of bio-methanol. About 29 million tonnes of bio-methanol can be produced from these biomass that have no commercial utilization (Nakagawa and Harada 2004). EFB generation capacity alone in Malaysia could produce about 3 million tonnes of bio-methanol which could

serve as transportation biofuel. Bio-methanol has promising application as raw material in biodiesel production since about 40 % of the raw materials (chemicals) are obtained from inorganic methanol.

The main aim of this section is to carry out an evaluation of the main environmental impacts of bio-methanol production from EFB using LCA tool. The process assessed in this study is tantamount to biomass-to-liquid (BtL) process for methanol production. In the palm oil mill, unlike PPF and PKS, the EFB, which are generated during the milling process are presently not utilized as boiler fuels in CHP plants of the mill. Other solid palm wastes like OPT, OPL etc. could be used as feedstock for bio-methanol production for sustainable development. Bio-methanol is one emerging transportation fuel used widely in the USA and EU but their feedstock is mostly straw and grain husks. Palm wastes have not been used on commercial scale production of bio-methanol hence the data used in this study was obtained from recently published research reports on other biofuels production systems (Renó et al. 2011; González-García et al. 2010; Huber et al. 2006).

Unlike methanol production from natural gas, bio-methanol production from palm wastes requires pretreatment of the biomass before gasification as well as the bio-syngas purification. According to Hamelinck and Faaij (2002), the main stages involved in bio-methanol production from biomass include:

- Pretreatment stage where the biomass is cleaned, dried and shredded into appropriate material sizes depending on the type of gasifier. The total energy usually required by the gasifier for size reduction and biomass drying (to about 10–15 % of moisture) are 0.1–0.15 and 2.3–2.4 MJ per kg biomass processed (Pierik 1995).
- Thermal treatment and Gasification of the pre-treated biomass in the presence of oxygen. At a particular temperature and conditions of gasifier operations, pyrolysis occurs yielding liquid and gaseous streams. Gasification that uses oxygen as the main gasifying fluid produces syngas with limited amount of nitrogen, which improves the quality of methanol produced.
- Syngas clean-up which removes chlorine, sulphur, particulate matter and other contaminants from the syngas. These impurities in the syngas cause fouling of tubes, tar accumulation and catalyst inactivation resulting in lower yield and quality of the methanol.
- Syngas conditioning whereby the syngas composition is adjusted for optimum methanol yield. During this stage, the ratios of $\text{CO}_2:\text{CO}$ and $\text{H}_2:\text{CO}/\text{CO}_2$ are adjusted to be 1:1 whilst the inert gases (N_2 and CH_4) concentrations are also reduced. These adjustments are effectively done through water gas-shift reaction (Chap. 2, Sect. 2.4) which converts the CO into H_2 and CO_2 ($\text{CO} + \text{H}_2\text{O} = \text{H}_2 + \text{CO}_2$) (Huber et al. 2006). The methane concentration in the syngas is also controlled by steam reforming using Ni catalyst at high temperatures between 800 and 1000 °C ($\text{CH}_4 + \text{H}_2\text{O} = 3\text{H}_2 + \text{CO}$) (Huber et al. 2006). Carbon dioxide removal by either physical or chemical means is also necessary at this stage to get good yield of methanol. However, at lower

temperatures below 800 °C, methane is formed at high quantities instead of high yields of syngas (H_2 and CO_2) (Boerriegter 2004).

- Methanol synthesis where the conditioned syngas is subjected to hydrogenation at high temperatures between 200 and 300 °C and pressure of 5–10 MPa with suitable catalyst (Barrañon 2006).
- Methanol purification where the water content of the methanol as well as other co-products are removed by distillation.

For clarity in assessing the environmental impacts, the palm bio-methanol production processes are divided into (1) Pretreatment (2) Gasification (3) Bio-syngas conditioning (4) Bio-ethanol synthesis and purification. Figures 2.6 and Figures 2.10 in Chap. 2 summarizes the BtL route for bio-methanol production were used as system boundary for this study. Again, the agricultural stage is not considered as it has been assessed already in the previous section (Sect. 5.4). The main inputs into the system are EFB, catalysts, steam, electricity and diesel for biomass processing into bio-methanol. The outputs are the products, co-products and emissions released from the various processes. Allocations were made based on energy content of the products and co-products hence the environmental loads were assessed using the heating values of the inputs and outputs (Olivério and Ribeiro 2006). A functional unit of 1 kg bio-methanol is chosen in order to make comparisons with the LCA of other palm biofuels in this study.

5.7.2 LCIA Results and Interpretation of Palm Bio-methanol Production

The energy efficiency of the palm bio-methanol production is assessed based on the NER and NEV with considerations of the amounts of inputs and outputs. In this case, about 2 kg EFB (about 40 MJ) is needed to produce 1 kg bio-methanol (about 23 MJ) which is quite inefficient. With regards to NEV and NER, it can be inferred from Appendix C, Table C.3 that about -3.35 MJ and 0.94 can be estimated from the inputs and outputs (including co-products and excluding emissions). The NRnEV was about 50.66 MJ which is regarded as positive due to the renewable source of energy and limited amount of fossil fuel used during the process. From this study, it can be concluded that about 8.67×10^{-5} MJ of fossil fuel is used to produce 1.0 MJ of bio-methanol from EFB. The energy efficiency of switch grass bio-methanol has been assessed to be between 26 and 60 %, which is quite lower compared to the energy efficiency of palm bio-methanol (~ 94 %).

Six out of the eleven impact categories were significant with acidification and eutrophication potential contributing the most (45.1 %). However, climate change (from fossil fuel use, soot from gasifier etc.) and ecotoxicity potentials (from chemicals) were negative signifying bad environmental impact. Fossil fuel use (38.9 %), respiratory inorganics (28.1 %) and carcinogens (4.4 %) potentials were

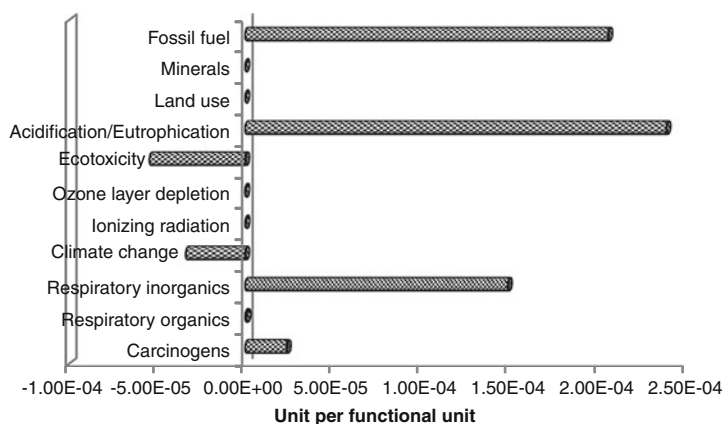


Fig. 5.13 Impact contributions from the impact categories on palm bio-methanol production via BtL route

among the significant impact categories. Minerals, ozone layer depletion and respiratory inorganic potentials were hardly noticeable. Figure 5.13 shows the environmental impact contributions of the various impact categories to palm bio-methanol production from EFB.

The gasification unit contributed the highest impact ($\sim 31\%$) followed by the methanol synthesis unit (23%). The pretreatment unit recorded the lowest impact of about 11% . Overall, resource use carried the highest impact followed by ecosystem depletion and human health with contributions of about 39 , 35 and 26% of the total impacts respectively. In the gasifier and methanol synthesis units, the generation of ash, tar and other pollutants resulted in significant environmental impacts to ecosystem depletion and human health. These can be reduced by using more advanced gas pollutant capturing systems like sorbents, filters etc. as well as employing a catalytic cracking process for the produced tar. The results from this study are similar to the report from Renó et al. (2011) who concluded that bio-methanol from sugarcane bagasse is net energy positive compared to gasoline production.

Figure 5.14 shows the emissions reduction from the combustion of 1 kg palm biodiesel, palm bioethanol and palm bio-methanol in their respective engines. Comparing these three types of palm biofuels, bio-ethanol has better emission reductions for all the potential emissions during combustion. Bio-methanol is better than biodiesel in terms of emission reductions though their values are closer to each other.

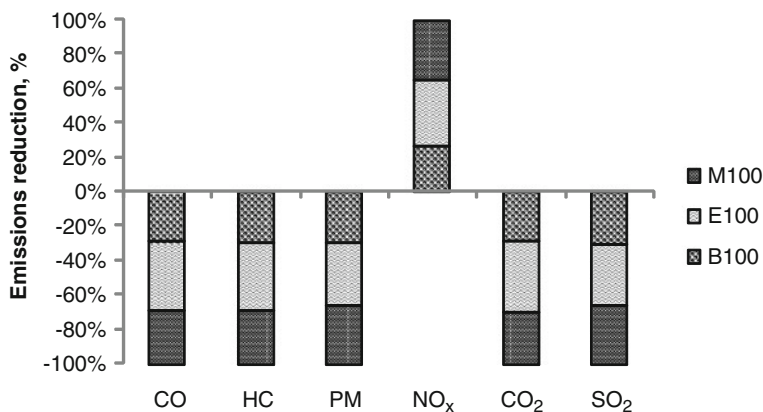


Fig. 5.14 Emission reduction of pure forms of liquid palm biofuels during combustion. B100, E100 and M100 represent pure form of biodiesel, bioethanol and bio-methanol without blends respectively

5.8 LCA of Simultaneous Production of Biogas and Bioelectricity from POME

5.8.1 Goal, System Boundary and LCI

This LCA study aims to assess the environmental impacts of biogas from POME as biofuel to feed gas turbines for steam and electricity production. The main unit to be studied is the anaerobic digester, which is used to simultaneously treat POME and produce biogas. In palm oil mills, about 70 % of the methane (a GHG) emissions come from POME and the capture of this biogas for energy production may reduce the emissions drastically. The evaluation of environmental impacts from NH₃, CH₄, N₂O and other emissions from POME disposal is highly relevant for the environmental sustainability assessment of biogas production. Figure 5.15 summarizes the system boundary of LCA of biogas production from POME.

The system boundary includes the combustion of biogas in gas turbines for bioelectricity production. The construction and maintenance of the digester (considered to be constructed with stainless steel), gas scrubbers and gas turbines were not taken into account. Energy inputs were calculated based on primary energy use whilst the net energy content in the biogas, bio-electricity and heat for a period of 20 years were used to calculate the output energy.

In most palm oil mills with POME treatment plant, the CHP plant is also constructed within the mills thus transportation of POME to digesters and biogas to CHP plant is not considered. The functional unit is 1 MJ biogas from POME. Four main steps are considered in this study for biogas production from POME namely:

- Anaerobic digestion of POME.
- Effluent (Digestate) treatment.

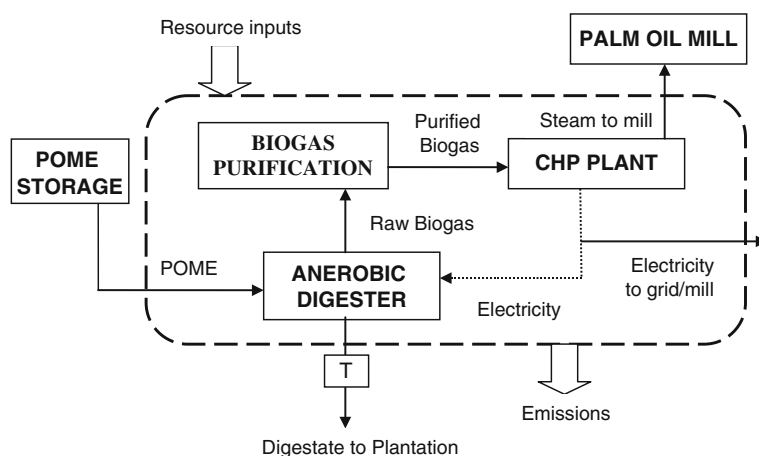


Fig. 5.15 System boundary of biogas and bio-electricity production from POME

- Biogas purification and storage
- Biogas combustion in gas turbines for electricity production (CHP plant).
- Digestate processing and discharge.

Some biogas plants may have separate homogenizing equipment different from the anaerobic digester. Most commercial anaerobic digesters are plug flow and complete-mix reactors which normally operate at mesophilic temperatures (37–40 °C). The generated raw biogas from the digester is impure of H_2S , CO_2 and H_2O , which need to be removed in order to improve the yield of CH_4 . H_2S is a corrosive and environmentally damaging gas which is often removed from the biogas by biological desulphurization in which a limited quantity of air is added to the biogas in the presence of specialized aerobic bacteria to oxidize the H_2S into elemental sulfur. Again, H_2S can be removed with the help of metal oxides, activated carbon, specialized bacteria etc. Biogas purification is done in order to remove sulphur and ammonia which are potential environmental damaging emissions. Again, CO_2 , which is another component of biogas must be removed in order to improve the energy density of the biogas and keep clean environment. During the purification process, a pressure swing adsorption process is used to remove CO_2 whilst biological filtration and thermal processes are used to eliminate sulphur and water vapour from the biogas respectively. Other technologies like membrane separation, water scrubbing (Ofori-Boateng and Kwofie 2009), pressure swing adsorption etc. can be efficiently employed to remove CO_2 from biogas. Water in the biogas can also be removed by drying using technologies like refrigeration, adsorption, absorption etc.

In the CHP plant, the purified and dried biogas is vented into a generator to produce heat and electricity. The Digestate is also dewatered, solar dried (for sustainable energy consumption) and conditioned into organic fertilizer. The

filtrate from the dewatering process is also treated using activated sludge process in which an aeration tank and clarifiers are used. The treated water can be recycled for use in the palm oil mill. Energy savings is highly achieved when an automated system (using remote control) for the monitoring of the process is used which facilitates rapid feedback and adjustments. Acid forming bacterial in the digester also convert volatile fatty acids in the POME into methane and CO_2 .

Biogas from POME consists of about 65 % CH_4 , 26 % CO_2 , 0.5 % N_2 , 0.3 % O_2 , 6 % H_2O , 2.67 % H_2S and 0.03 % NH_3 (O-Thong et al. 2012). POME from CPO milling unit is pumped directly into a continuously stirred digester with mesophilic anaerobic microbes operating at 40 °C. During anaerobic digestion of POME, three processes occur simultaneously. First, facultative bacteria operating in the digester break down the complex molecules into their simplest forms with the help of oxygen and water through a process called hydrolysis. Subsequently, the substrates from the hydrolysis stage are converted to acetic acid, CO_2 , H_2 and volatile fatty acids by acidogenic bacteria. Methanogenesis then occurs whereby the products from the acidogenesis stage are converted into biogas by thermophilic bacteria. The biogas produced is then sent to the purification unit for scrubbing. The treatment of 1 m^3 of POME (~1500 kg) can generate approximately 28 m^3 of biogas at optimal conditions with energy content of about 20 MJ/m^3 . It is assumed that all the biogas produced (1 MJ) is used for co-generation for approximately 1.7–2.5 kWh electricity and 7.8 MJ heat. Electricity consumption by the digester (including stirring and pumping of POME) is estimated at about 3.6 MJ per m^3 of biogas generated. Emissions from electricity consumption are obtained from Ecoinvent database.

The LCI of this study gives the results of input and output resources as well as emissions associated with the entire life cycle of 1 MJ biogas from POME. Emissions such as CO_2 , N_2O and CH_4 are regarded as outputs in the LCI for biogas production (see Appendix B, Table B.1). Data were collected from published literature, statistical data and Eco invent database. Biogas being the main product in this study would be the focus of environmental impacts. Bio-electricity and heat generated from the biogas are better replacement alternative for fossil fuels whilst the scrubbed biogas would be suitable as transport fuel. The digestate (slurry) is an organic fertilizer with high superphosphate content which could be used in the oil palm plantation. A palm oil mill which produces about 65,000 tonnes of CPO annually is assessed by Shiraj et al. (2003) to have a potential electricity generation of about 8.2 GWh from the POME that is produced as wastes.

5.8.2 LCA Results and Interpretation: Biogas and Bio-electricity Production from POME

The main resource inputs to the biogas and bio-electricity production system were POME, activated carbon and electricity from fossil fuel. With a total input energy

usage of 76.11 MJ, about 2.13 MJ outputs (biogas and bioelectricity) was obtained. About 2.678 kg (~ 57 MJ) of POME was used to generate 1 MJ of biogas and ~ 0.31 MJ of bio-electricity (see Appendix D, Table D.1). The NEV and NER for the system were about -25.615 and 0.66 MJ respectively. The reason for such a low NER for the system is the high-energy value contribution of POME (57.34 MJ) to the input resources' energy for the generation of the biogas which was of comparatively low energy value (1 MJ). However, the slurry (co-product) from the digester is considered for utilization as bio-fertilizer in the oil palm plantation otherwise, the NER value for the production system would have been as low as 0.028 MJ. Commercial scale production of biogas from POME would help increase the NER value. The amount of fossil fuel used during the processing of POME into biogas and bio-electricity was very low which increased the renewability of the system to about 50.31 MJ. The NRnEV would be high if bio-electricity generated from the biogas plant or CHP plant in the palm oil mill was used as the main energy input into this production system.

Three (3) out of the eleven impact categories were significant for the bio-electricity generation from POME. Climate change potential contributed about 98% of the total impacts with acidification/eutrophication and fossil fuels use potentials significantly contributing about 1% each. Climate change potential impacts resulted from the traces of emissions of CH_4 , H_2S , CO , CO_2 , particulate matter etc. from the combustion of the biogas.

The highest impact came from the combustion of biogas into bio-electricity (about 59%) where traces of the air pollutants were emitted into the atmosphere though larger percentage of the co-products (H_2S and CO_2) were captured. Combustion and equipment efficiencies of the gas turbines would help reduce these emissions. The gas purification unit was the next highest (23%) contributing unit to climate change, fossil fuel use, respiratory inorganics, acidification/eutrophication potentials. Inefficiencies in equipment and process designs as well as inappropriate gas capture would contribute to high potential environmental impacts. The biogas production unit (anaerobic digester) was the most efficient unit with less environmental impact contributions (19%). If open ponds would have been used to treat the POME without proper biogas capture, the potential environmental impacts would have been higher.

5.9 Conclusion

LCA studies for four major palm biofuels production systems were assessed. For palm biofuels feedstocks production for palm biodiesels based on 1 kg functional unit for each subsystem, the oil palm nursery (for a single seedling) emerged as the least energy efficient with high environmental impacts. The palm oil milling processes for the production of crude palm oil were the next highest contributors to the total environmental impacts during the palm biodiesel production. PFAD biodiesel production emerged as the most efficient and less environmentally

damaging production system compared to all the other types of palm biodiesel that were assessed in this chapter. All the palm biofuels that were assessed in this chapter were found to have better combustion characteristics and high GHG emissions reductions.

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Chapter 6

Economic Sustainability Assessment of Biofuels Production from Oil Palm Biomass

Abstract The production of palm biofuels provides the prospects for new economic opportunities for most people in rural communities in developing countries. Oil palm cultivation and palm oil milling provide wide avenues for people in terms of job creation, investment opportunities, etc. In spite of all the benefits of palm biofuels, they are also found to cause negative socio-economic impacts to the society. The economic impacts of oil palm and palm biofuels production are elaborated in this chapter. Oil palm biomass is a cheap source of feedstock for palm biofuels compared to other feedstocks used for biofuel production. In this chapter, biodiesel production from palm oil and palm fatty acid distillate (PFAD) are found to be economically viable compared to fossil diesel and biodiesel from other oils. Bioethanol and biomethanol production from oil palm biomass are also found to be cost competitive compared to gasoline and other cellulosic ethanol. Other potential types of palm biofuels are assessed for economic sustainability and improvement options are also suggested in this chapter.

Keywords Economic sustainability • Sustainable development • Palm biofuels • Life cycle cost • Economic impact assessment • Oil palm cultivation • Palm biodiesel • Palm bioethanol • Palm oil mill effluent • Oil palm wastes

6.1 Introduction

A system is termed economically sustainable when it is capable of containing or adapting to the conditions of the ecosystem on which it depends. The integration of economic sustainability with social and environmental aspects of sustainability helps generate long-term profit for the society. A society, which does not deplete the ecosystem's resources and services but rather maintain the natural resources through energy efficient methods for the future generation to benefit, is said to be economically sustainable. In such a society, wastes are treated as economic resources at appropriate places and periods and waste minimization criteria may

include small environmental penalties, low liability insurance, achieving savings from waste disposal cost, etc., which eventually lead to high market shares. Sustainability for the palm biofuel industry would be achieved through strategic means and technologies of breaking the linkage between negative economic impacts, environmental damages, and resource depletion.

Economic analysis is a major driving force, which supports the development of process technologies, and it can be used to predict the cost of a production plant through different process conditions and assumptions (You et al. 2008; Marchetti and Errazu 2008). Conventional economic sustainability assessment is centered mainly on economic growth and efficient allocation of resources while ecological economics focuses more on sustainable development, equitable distribution, and efficient allocation of resources. Nowadays, discussions and debates on economic sustainability focus on increasing the stock of man-made capital while decreasing other capital stocks to some degree (OECD 2001). Economic analysis results could help design policies that are used to govern the sustainability of biofuel production systems. Economic assessment results are again needed to evaluate the social cost and benefits of biofuel policies like tax credits, mandates, import tariffs, etc.

The palm oil industry, which is the sole source of feedstock for palm biofuels, is a notable agricultural industry with high economic gains in many tropical countries like Indonesia and Malaysia. For instance in Malaysia, the palm oil industry contributes about 8 % of the nation's gross national income (GNI) per capita (PEMANDU 2010). However, Mumtaz et al. (2010) and Tan et al. (2010) have reported that though the oil palm remain the cheapest source of vegetable oil in the world, it is still inefficient in terms of cost when used especially for biofuels production. In the world presently, the relationship between energy prices and palm oil cost has been strong due to the increasing use of competing feedstocks for biofuels production and this has introduced a new paradigm for price volatility, which pose problems for smallholders. Though other factors determine the cost efficiencies of biofuel production systems, the cost of feedstock remain the major contributing factor, which needs to be improved. Most of the techno-economic assessments of biofuel production systems have excluded the economics of the feedstock production stages and have used the ex-factory prices of the feedstocks in their studies. However, the feedstock cost for palm biodiesel production for instance form about 70–80 % of the total production cost (Ong et al. 2012; Jegannathan et al. 2011) and it would be economically challenging to produce cost-effective biodiesel when the feedstock price becomes extremely higher. In such an instance, the government has to come in to support the biofuel industry in terms of subsidies and incentives in order to produce and market palm biofuels effectively. In view of this, Malaysia and Indonesia have collaborated and agreed to allocate about 40 % of their palm oil for palm biodiesel to replace fossil diesel in the near future.

The aim of this chapter is to identify various socio-economic impacts of palm biofuel production processes on the communities and as well assess the economic sustainability of palm biofuel production systems from different reports.

6.2 Economic Sustainability Assessment of Biofuels from Oil Palm Biomass

Many authors have assessed the economics of biofuel production systems which utilize oil palm biomass as feedstocks based on different economic indicators. However, three main economic factors are of great concern namely capital cost, operating cost, and maintenance cost. From these three factors or parameters, other cost benefit indicators can be assessed. The cost–benefit analysis of a biofuel production plant can be evaluated using various tools and techniques such as life cycle cost (LCC) analysis, Aspen Plus, Aspen HYSYS, etc.

With LCC analysis, the cost–benefit assessment can be done based on six factors as defined by Eq. (6.1):

$$\begin{aligned} \text{LCC} = & \text{capital cost (CC)} + \text{operating cost (OC)} + \text{maintenance cost (MC)} \\ & + \text{feedstock cost (FC)} - \text{salvage value (SV)} - \text{byproduct credits (BP)} \end{aligned} \quad (6.1)$$

Equation (6.1) can be rewritten in a form of a present value (Eq. (6.2)) whose calculations are widely used in business and economics to evaluate and differentiate cash flows at different times.

$$\text{LCC} + \text{CC} + \sum_{i=1}^n \frac{\text{OC}_i + \text{MC}_i + \text{FC}_i}{(1+r)^i} - \frac{\text{SV}}{(1+r)^n} - \sum_{i=1}^n \frac{\text{BP}_i}{(1+r)^i} \quad (6.2)$$

where LCC = life cycle cost, CC = capital cost, OC = operating cost, MC = maintenance cost, FC = feedstock cost, SV = salvage value, BP = by product credits, r = interest rate, i = number of years, n = plants life time.

Alternatively, the LCC can be found from the initial investment cost (C_i), annual payments (such as fuel cost, maintenance, and operation costs) which is discounted at their present value (P_{Vr}) and the cost of replacements discounted at their present value (P_{Vs}) as defined by Eqs. (6.3) and (6.4).

$$\text{LCC} = C_i + P_{Vr} + P_{Vs} \quad (6.3)$$

$$\text{LCC} = C_i + \left[\sum_1^n C_{ap} \cdot \left[\frac{x(1-x)}{1-x} \right] \right] + \left[C_s \cdot \left[\frac{1+i}{1+d} \right]^n \right] \quad (6.4)$$

where C_i = initial investment cost, C_s = single future cost, P_{Vr} = recurring annual payment, P_{Vs} = single future payment, $x = (1+i)/(1+d)$, i = interest rate, d = discounted rate, n = number of years for which the payment is made.

The LCC results can be expressed in terms of cost per annum by reverse of discounting called the annualized life cycle cost (ALCC). In another instance, the results could be expressed in levelized cost (Eq. (6.5)) which defines the LCC in terms of total production or unit energy cost over the project's life.

$$\text{Levelized cost} = \frac{\text{LCC}}{\text{TBP}} \quad (6.5)$$

where LCC = life cycle cost and TBP = total biodiesel production.

The future cash flow can also be gathered in order to attain the current present value of the production system, which is mostly represented by the Present Worth Factor (PWF). This factor is capable of justifying the feasibility or sustainability of the biofuel production system at a particular interest rate and can be written for a year, i by Eq. (6.6):

$$\text{PWF} = \frac{1}{(1 + r)^i} \quad (6.6)$$

where PWF = present worth factor, r = interest rate, i = number of years.

Equation (6.7) defines the compound present worth factor of a plant whose life is n years:

$$\text{CPW} = \sum_{i=1}^n \frac{1}{(1 + r)^i} = \frac{(1 + r)^n - 1}{r(1 + r)^n} \quad (6.7)$$

where CPW = compound present worth, r = interest rate, i = number of years, n = plants life time.

The capital cost of palm biofuel plant consists of the cost of construction, equipment, and instrumentation, which depend on the biofuel plant capacity. Howell (2005) has reported that high biofuel plant capacities require high initial capital cost. For instance, an estimated capital cost of US\$15 million is required to put up a biofuel production plant with capacity of 70,000 tonnes (Howell 2005).

Operating costs include the cost of labor, utilities, laboratory services, supervision, transportation, factory expenses, administrative costs, as well as all other material and energy flows into the plant. When all the waste streams in the plant are considered to be treated before discharge, then the costs involved during these processes are part of the operating costs. With a known operating rate (OR) (US\$/tonne biodiesel), the total operating cost can be calculated using Eq. (6.8):

$$\text{TOC} = \text{OC} + \sum_{i=1}^n \frac{\text{OR} \times \text{PC}}{(1 + r)^i} \quad (6.8)$$

where TOC, OC, OR, and PC represent the total operating cost, operating cost, operating rate, and annual biodiesel production capacity, respectively; r = interest rate, i = number of years, n = plants life time.

The maintenance cost (MC) of a plant is mostly the cost associated with the repair, renovation, services, and other maintenance activities carried out on the plant and this is mostly taken as a specific percentage of the initial capital cost. The MC can also be calculated using Eq. (6.9):

$$MC = \sum_{i=1}^n \frac{MR \times CC}{(1+r)^i} \quad (6.9)$$

where MC, MR, CC, r , n , and i represent the maintenance cost, maintenance ratio, capital cost, interest rate, project life, and year, respectively.

The annual consumption of feedstock over the life of the plant can be found using Eq. (6.10) when feedstock price and feedstock costs are known.

$$FC = \sum_{i=1}^n \frac{FP \times FU}{(1+r)^i} \quad (6.10)$$

where FC, FP, and FU represent feedstock consumption, feedstock price, and feedstock cost, respectively; r = interest rate, i = number of years, n = plants life time.

The salvage value is the remaining value of the components and other assets of the plant at the end of the project's lifetime. Depending on the depreciation rate, a model based on the replacement cost rather than the initial capital cost can be used to find the salvage value Eq. (6.11) and the present value of the salvage cost Eq. (6.12):

$$SV = RC(1-d)^{n-1} \quad (6.11)$$

$$SV_{PV} = \frac{RC \times (1-d)^{n-1}}{(1+r)^n} \quad (6.12)$$

where SV, RC, and SV_{PV} represent salvage value, replacement cost, and present value of salvage cost, respectively; r = interest rate, d = depreciation ratio, n = plants life time.

Byproduct credit refers to the amount of money obtained after the sales of all the co-products generated during the processing of oil palm into biofuels. For instance, in the mill and biodiesel production unit, co-products like palm kernel cake and glycerin can be sold, respectively to add to the profits of the plant. For instance in the palm biodiesel production unit, glycerin price can be fixed in order to determine the byproduct credit using the plant capacity and glycerol conversion factor over the life of the plant Eq. (6.13):

$$BP = \sum_{i=1}^n \frac{GP \times GCF \times PC \times 1000}{(1+r)^i} \quad (6.13)$$

where BP, GP, GCF, and PC represent byproduct credit, byproduct price, byproduct conversion factor from feedstock oil, and annual biofuel production capacity, respectively; r = interest rate, i = number of years, n = plants life time.

Payback time is the time taken to obtain a financial return that is equal to the original investment cost. Payback time is one of the factors used to determine the feasibility or sustainability of the production plant. Equation (6.14) can be used to determine the payback time of a plant.

$$PP = \frac{CC}{TBS - TPS - TAX} \quad (6.14)$$

where PP is the payback period, TBS is the annual total biofuel sales, TPC is the annual total production cost, and TAX is the annual total tax.

Using Aspen Plus for economic assessment of a production plant, a model defined by Eq. (6.15) is able to estimate the bare model equipment cost in order to find the total capital cost (including the direct and indirect costs) (Turton et al. 2009):

$$C_{BM} = C_p^0 F_{BM} \quad (6.15)$$

where C_{BM} and F_{BM} are the bare module cost and bare module factor, respectively.

The purchase cost for base conditions, C_p^0 , can be calculated using Eq. (6.16)

$$\log_{10} C_p^0 = K_1 + K_2 \log_{10}(A) + K_3 [\log_{10}(A)]^2 \quad (6.16)$$

where C_p^0 is the purchase cost, K_1 , K_2 , and K_3 are constants to the equipment type; A is the parameter for the capacity or the size of the equipment. The bare module cost factor, F_{BM} , the operating pressure and the construction materials are calculated using Eq. (6.17):

$$F_{BM} = B_1 + B_2 F_M F_P \quad (6.17)$$

where B_1 and B_2 are constants which depend on the type of equipment, F_M is the material factor which depend on the equipment type. F_P is the pressure factor, which is defined by Eq. (6.18):

$$\log_{10} F_P = C_1 + C_2 \log_{10} P + C_3 (\log_{10} P)^2 \quad (6.18)$$

where C_1 and C_2 are constants depending on the type of equipment and material it is made of. Other important factors which cannot be found in the database of Aspen Plus could be found from Lim et al. (2009) and Turton et al. (2009) who have calculated for parameters like K_1 , B_1 , C_1 , etc. The total manufacturing or production cost can then be estimated based on mass balance, raw material costs, utility costs, operating labor, etc. (Turton et al. 2009).

Economic sustainability assessment of a production plant involves the evaluation of four major economic factors namely total capital investment (TCI), total production cost (TPC), profitability, and sensitivity indicators. TCI includes the amount of money required to finance the purchasing of equipment as well as its auxiliary parts, spare parts, construction of the plant, and the acquisition of items necessary for plant operation. TCI comprises of fixed capital investment (FCI) and working capital (WC). The FCI also called as the bare module cost (C_{BM}) is the cost involved or investment needed to supply all production facilities as well as supply of construction overheads and plant components that are directly or indirectly related to the production processes. WC is the amount of money needed to start the project. This is mostly estimated as 0.15 times the fixed capital investment

(Sinnot 1986; Peters and Timmerhaus 1981). Total capital cost may include costs of land, equipment and installations, building and construction costs.

The total production cost involves the cost needed to run the project including marketing of the products. This indicator generally consists of the variable cost, fixed costs, and general expenses. Variable cost consists of direct and indirect costs. Generally, variable cost may include costs of raw materials, utilities, miscellaneous materials, shipping and packaging, etc. Fixed costs also include the cost of maintenance, operating labor, supervision, plant overheads, capital charges, Insurance rates, and Royalties. General expenses are made up of administrative costs, engineering and legal costs, office maintenance and communications, distribution, and selling cost (Prueksakorn et al. 2010; Jain and Sharma 2010).

The methods used in estimating the profitability of the project are rate of return on investment (ROI), payback period, breakeven point, discounted cash flow rate of return (DCCFRR), and the net present/future value. These indicators can clearly justify the economic feasibility of a production plant.

The ROI is defined as the ratio of the average cumulative cash flow to the total initial investment expressed as a percentage. This indicator is mathematically defined by Eq. (6.19) (Sinnot 1986):

$$\text{ROI} = \frac{(\text{cumulative net cash flow at end of plant life})}{(\text{plant life}) \times (\text{initial investment})} \times 100\% \quad (6.19)$$

Payback period is the minimum length of time theoretically necessary to recover the original investment, without interest in the form of cash flow to the project based on total income less all costs excluding depreciation. Equation (6.20) defines the payback time mathematically (Sinnot 1986):

$$\text{payback period} = \frac{(\text{depreciable fixed capital investment})}{(\text{average profit}) + (\text{average depreciation})} \quad (6.20)$$

The net present worth (NPW) also called as the net present value (NPV) accounts for the time value of money. The money earned in any year can be put to work (reinvested) as soon as it is available and start to earn a return. Thus, money earned in the early years of the project is more valuable than that earned in later years. This time value can be allowed for by using a variation of the familiar compound interest formula. The net cash flow in each year of the project is brought to its present worth at the start of the project by discounting it at some chosen compound interest rate (Tomomatsu and Swallow 2007). The discount rate is chosen to reflect the earning power of money. It would be roughly equivalent to the current interest rate that the money could earn if invested. Equation (6.21) defines the NPW (Sinnot 1986):

$$\text{net present worth (NPW)} = \frac{\text{estimated net cash flow in year } n \text{ (NFW)}}{(1 + r)^n} \quad (6.21)$$

where r = the discount rate (interest rate) in percentage. Equation (6.22) (Sinnott 1986) also expresses the total NPW mathematically:

$$\text{Total NPW of project} = \sum_{n=1}^{n=t} \frac{\text{NFW}}{(1+r)^n} \quad (6.22)$$

where NFW = the future worth of the net cash flow in year n , t = the life of the project, years

Break-even point (BEP) is the time of the plant's life where there is neither net profit nor net loss. It is the level above which the production rate must be exceeded in order to make profit. The break-even point would vary as the sales and manufacturing cost varies over the years. Equation (6.23) defines break-even point:

$$\text{BEP} = \frac{\text{fixed costs}}{\text{total sales} - \text{variable cost}} \times 100 \quad (6.23)$$

DCFRR is used to calculate the present worth of future earnings and it is sensitive to the interest rate. By calculating the NPW for various interest rates, it is possible to find an interest rate at which the cumulative net present worth at the end of the project is zero. This particular rate is called the DCFRR and is a measure of the maximum rate that the project could pay and still break even by the end of the project life. Equation (6.24) defines DCFRR mathematically:

$$\text{DCFRR} = \sum_{n=1}^{n=t} \frac{\text{NFW}}{(1+r')^n} = 0 \quad (6.24)$$

where r' = the discounted cash-flow rate of return in percentage,

NFW = the future worth of the net cash flow in year n ,

t = the life of the project, years.

Normally, it is best to carry out sensitivity analysis for biofuel production plants in order to identify critical input resources or factors and assess their variability impacts on the LCC or economic analysis results. Sensitivity analysis is carried out on production plants to evaluate the variation of the projected performance of the plant with the main assumptions and conditions to which the projections are based. The uncertainty in the economics of the projects that are capable of affecting the outcomes of the plant are also assessed during sensitivity analysis (Gunawan et al. 2005). For palm biofuel production, factors like oil palm biomass price, interest rate, capital cost, etc., are vital to be selected appropriately in order to remove as much uncertainties that may result from the economic assessment. The palm feedstock price is highly sensitive to the cost of the biofuel produced and whenever the rate of feedstock growth outweighs that for biofuel production, the feedstock price may fall because there may be no request for them and vice versa when biofuel production capacity grows ahead of the palm feedstock.

6.2.1 Oil Palm Cultivation and Palm Oil Milling

Budidarsono et al. (2012) have assessed the economic sustainability of palm oil production for 23 plantations based on four economic components namely capital cost, labor requirement, profitability, and economic returns. The total production cost took into account the profit for every tonne of crude palm oil (CPO) and palm kernels processed.

The returns obtained from the economic analysis were higher than the average agricultural wage rate (US\$3.27–4.67 per person per day) and this implies that oil palm agriculture is attractive to farmers. Out of the 23 plantation assessed, 13 were able to reach positive cash flow in year six or earlier. A total capital investment cost was estimated to be US\$2,054 per hectare, which is very high for smallholders to attain without financial support. During the establishment, maintenance and harvesting stages of large-scale oil palm cultivation with high potential profitability, high labor force in the range of 332–2,542 persons/day/ha is required (Budidarsono et al. 2012). The returns to land and labor for smallholders over a 25-year period were US\$9,044–14,059 per hectare and US\$12–17 per person per day, respectively.

Palm oil cultivation on mineral soils is profitable with high returns to labor compared to cultivation on peat lands (Budidarsono et al. 2012). Peat lands also require high initial capital investment with labor requirements of about 683 persons/day/ha which is about 4 % higher than cultivation on mineral soils (Budidarsono et al. 2012). Figure 6.1 shows the net present value and initial capital investment for oil palm cultivation on mineral soils and peat lands.

Budidarsono et al. (2012) again concluded that palm oil processing is profitable with a NPV for a 15-year investment ranging from US\$13.8 to 102.9 million. For a tonne of CPO produced with credits from palm kernels, there is a profit of US\$43–164. Budidarsono et al. (2012) have assessed the production of palm oil to

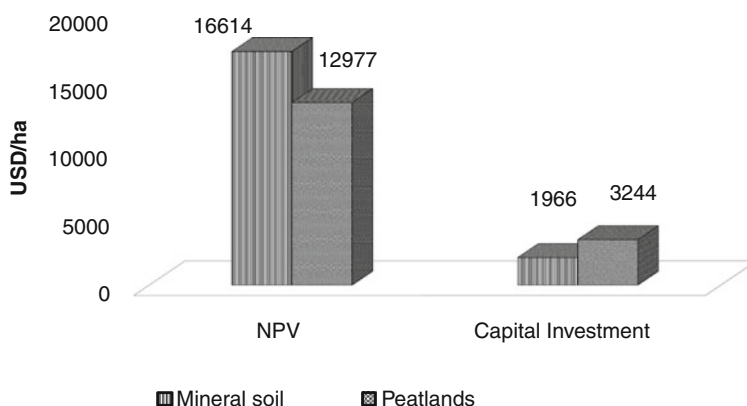


Fig. 6.1 NPV and capital investments for oil palm cultivation on peat lands and mineral soils

be economically sustainable when there is constant flow of fresh fruits from the plantation assess palm oil production.

6.2.2 Biodiesel Production from Crude Palm Oil

Many authors (Ong et al. 2012; Jegannathan et al. 2011; Quintero et al. 2012; Mulugetta 2009; Cho et al. 2012; Lozada et al. 2010) have assessed the economic feasibility of biodiesel production from crude palm oil (CPO) and palm fatty acid distillate (PFAD) in different regions of the world.

Ong et al. (2012) used the methodology of life cycle cost (LCC) to assess the cost benefit of biodiesel production from palm oil based on a 50,000 tonnes of biodiesel plant located in Malaysia. Based on 10 % annual depreciation, 8 % interest rate, 15 % tax on biodiesel sales, palm biodiesel conversion efficiency of 98 %, and byproduct credit of US\$0.25/kg, they estimated the palm biodiesel cost to be US\$0.632/liter with a payback period of 3.52 years. In Malaysia, the retail price for fossil diesel is US\$0.58 per liter, which is lower than palm biodiesel as estimated by Ong et al. (2012). For a liter of palm biodiesel produced, the estimated crude palm oil cost, operating cost, maintenance cost, salvage value, and glycerin credit were US\$0.499, 0.131, 0.002, 0.0003, and 0.012, respectively. Palm oil price was about 79 % of the total production cost and it can be projected that any increase in the palm oil price by at least US\$0.10/kg would cause a rise in palm biodiesel by US\$0.05/liter (Ong et al. 2012). Thus, palm oil is a sensitive variable in determining the overall palm biodiesel cost (Huang et al. 2009). For a total production cost of US\$665.15 million for palm biodiesel plant, the operating cost formed about 21 %, which makes it another important contributing factor (after palm oil price) to the cost of palm biodiesel. The sustainability of production plants have always improved when wastes are converted into value-added bio-products. For a 20-year life of the palm biodiesel production plant, about US\$12.33 million was obtained from the sales of glycerol, which contributed to the decrease in the biodiesel cost. Apart from the palm oil price, which was highly sensitive to the palm biodiesel cost, interest rate was also a determining factor. Though interest rate cannot be changed by the biodiesel industry, there are other dependent variables like biodiesel conversion efficiencies, waste conversion, etc., that could improve the sustainability of the palm biodiesel plant. The production of biodiesel from palm oil is found to be economically sustainable as the payback time was less than one-third of the plant's life (Ong et al. 2012).

Lozada et al. (2010) have assessed a palm biodiesel production plant in Mexico with an annual capacity of 37.9 million liters/year (~34,000 tonnes/year) for economic viability. In their work, with palm oil price of US\$0.289 per liter and total operating cost of US\$0.369 per liter palm biodiesel, the cost of biodiesel produced was US\$0.37 per liter which is almost half the price of biodiesel obtained from 50,000 tonnes/year capacity plant (Ong et al. 2012). Usually, higher capacity production plants should produce cost effective productions compared to

small plants but in this case, it did not follow the trend. This implies that the cost of biodiesel depends on the location of the production plant as well as other basic assumptions and conditions. Though Malaysia is the second largest producer of palm oil in the world presently, hence a possible location of obtaining cheap source of palm biodiesel feedstock, other economic conditions in the country may increase the production cost of palm biodiesel. Mexican biodiesel is seen to be cheaper than Malaysian biodiesel both produced from palm oil. As seen from the work of Ong et al. (2012), interest rate is a sensitive variable that affects the cost of palm biodiesel produced in Malaysia.

Quintero et al. (2012) have done an extensive comparative economic assessment of biodiesel production from palm oil and *J. curcas* oil for different scenarios in Peru using Aspen Icarus Process Evaluator as the simulation software. The oil palm cultivation¹ and palm oil milling stages were excluded from their studies but based on previous research results the average cost of palm oil² was used to simulate the cost benefits of the biodiesel production system. For a plant capacity of 49 million liters (~43,000 tonnes) of biodiesel per year operating for 30 years, an estimated operating or production cost of US\$0.227–0.314/liter biodiesel was obtained for two scenarios.³ This cost is lower than the production cost of fossil diesel at US\$0.5/liter (EIA 2011) hence, palm biodiesel is a cost-effective alternative to fossil diesel. However, the selling of glycerin generated as co-product from the plant would reduce the total production cost by 12 % (Quintero et al. 2012). With an interest rate of 18 % and tax rate of 30 %, the average cost of palm biodiesel was estimated to be US\$0.27 (with an ex-factory price 1.91/liter) which is about three times lower than that for *J. curcas* oil biodiesel (Quintero et al. 2012; Amigun et al. 2008) and rapeseed oil biodiesel (Apostolakou et al. 2009). The production of palm biodiesel is also found to generate about 7,534 direct jobs for every 43,000 tonnes capacity plant in Peru (Quintero et al. 2012). Palm biodiesel in Peru is found to be economically viable with high ratio of sale price⁴ to production cost at 5.97–8.37 (Quintero et al. 2012). The production of biodiesel from palm oil either on small- or large-scale is profitable as compared to jatropha biodiesel and when it is not considered for subsidies, it is still a competitive alternative to fossil fuel in terms of cost (Quintero et al. 2012). Generally, the major factors which affect the cost of palm biodiesel are raw material cost, production cost, and capital depreciation (Huang et al. 2009) of which the feedstock cost (palm oil) is the major contributor. The cost of palm oil forms

¹ The agricultural cost per tonne of oil palm fresh fruit bunch (FFB) from smallholders and big companies were US\$46.99 and 22.32, respectively, according to the studies of Quintero et al. (2012).

² The price of palm oil from a commercial mill that generates its own electricity from the palm wastes was US\$92.50 (ex-factory price).

³ Scenario 1: Both smallholders and commercial producers; Scenario 2: Only commercial producers.

⁴ Palm biodiesel price is lower (US\$1.33) than the prices of soybean oil biodiesel (US\$1.42) (Quintero et al. 2012) and jatropha biodiesel (US\$1.96) (Quintero et al. 2012).

about 73–79 % of the total production cost of palm biodiesel (Ong et al. 2012; Quintero et al. 2012).

In Ghana, palm biodiesel production was assessed to be economically viable only when the fossil diesel price falls below US\$0.70/liter though the levelized palm biodiesel cost was estimated to be US\$0.40–0.78/liter (Mulugetta 2009). With 9 % discount rate, palm oil cost, which was about 75 % of the total production cost, was found to be the dominant factor in determining the biodiesel cost. In 2004, with oil palm seed cost of US\$160 per tonne, an annual operating cost of producing palm biodiesel was estimated at about US\$112.6 million of which palm oil accounted for over 85 % (Mulugetta 2009). However, as suggested by many authors, the sales from co-products of the palm biodiesel plant may reduce the over production cost.

Jegannathan et al. (2011) have carried out the economic analyses of different methods of producing biodiesel from palm oil. In their studies, palm oil cost was US\$0.56/kg ($\sim$ US\$0.493/liters). Based on a 1000 tonne capacity plant for palm biodiesel production using alkaline, soluble enzyme, and immobilized enzymes as catalyst for the transesterification reaction, about US\$634,000–997,000 was estimated as the total plant cost including operation costs. Alkaline catalyzed transesterification method evolved as the cost-effective method for producing palm biodiesel with a total production cost of about US\$1166.67 which is about seven times and two times less than the plant utilizing soluble enzyme and immobilized enzymes as catalyst, respectively.

The economic analysis of 8,000 tonne/year capacity plant for producing biodiesel from palm fatty acid distillate (PFAD) has been investigated by Cho et al. (2012) using Aspen Plus software. A noncatalytic esterification process was used to convert the PFAD into biodiesel, which attracted a capital investment of US\$1.63 million per year. This cost is about 21 % more than the capital investment required for alkaline-catalyzed transesterification of wastes cooking oil (WCO) (Zhang et al. 2003) but about 22 % less than that of supercritical process for biodiesel production (He et al. 2007). Some contributing factors to the high investment cost for biodiesel production from PFAD include the slow rate of reaction and high-pressure requirement.

The total production cost for the PFAD biodiesel production plant was estimated at US\$8.59 million per year which is also about 25 % less than alkaline catalyzed and supercritical processes for similar plant size (Cho et al. 2012). PFAD is a very cheap source of feedstock which when utilized for biodiesel through the alkaline catalyzed process, would be economically viable. Table 6.1 summarizes the economic assessment of various biodiesel production plants.

Generally, palm biodiesel production plants are economically viable compared to many biodiesel produced from other feedstocks like rapeseed oil and soybean oil. However, tax-exemption policies to support palm biodiesel would make them the best alternatives for fossil diesel. You et al. (2008) and Haas et al. (2006) estimated the cost of soybean oil biodiesel to be about US\$0.78 per liter and US\$0.53 per liter, respectively, when the conventional alkaline catalyzed transesterification was used. Comparing these costs to palm biodiesel of similar

Table 6.1 Comparative economic analysis of biodiesel production from different feedstocks

Plant capacity (tonnes/yr)	Location	Type of catalyst	Feedstock	Feedstock cost (US\$/l)	Biodiesel cost (US\$/l)	Glycerol credit (US\$/tonne)
1000 ^a	India	Alkaline	Palm oil	0.493	1.857	100,000
1000 ^a	India	Soluble enzyme	Palm oil	0.493	2.908	100,000
1000 ^a	India	Immobilized enzyme	Palm oil	0.493	2.920	100,000
50,000 ^b	Malaysia	Alkaline	Palm oil	0.499	0.632	—
34,000 ^c	Mexico	alkaline	Palm oil	0.289	0.370	33,500
43,000 ^d	Peru	Alkaline	Palm oil	—	0.270	—
—	Ghana ^e	Alkaline	Palm oil	—	0.590	—
52,800 ^f	—	Alkaline	Palm oil	0.730	0.880	0.120 ^g
62,480 ^f	—	Alkaline	Palm oil	0.730	0.860	0.120 ^g
125,840 ^f	—	Alkaline	Palm oil	0.730	0.820	0.120 ^g
8000 ^h	Korea	Non-catalytic esterification	PFAD	0.376	0.832	—
36,000 ^b	Argentina	Alkaline	WCO	445 ^h	0.510	73,800
36,000 ⁱ	Argentina	Supercritical	WCO	905 ^h	0.980	67,500
8000 ^j	Canada	Alkaline	WCO	525 ^h	0.950	91,300
7300 ^k	Japan	Alkaline	WCO	248 ^h	0.580	—
50,000 ^l	Greece	NA	Rapeseed oil	1158 ^h	1.150	—
8000 ^m	Denmark	Enzyme	Rapeseed oil	3042 ^h	2.040	2215,000
36,000 ⁿ	USA	Alkaline	Soybean oil	486 ^h	0.530	35,800
8000 ^p	USA	Alkaline	Soybean oil	779 ^h	0.780	380,000
62,031 ^f	—	Alkaline	Tallow fat	0.400	0.640	0.120 ^g

^a Jegannathan et al. (2011)

^b Ong et al. (2012)

^c Lozada et al. (2010)

^d Quintero et al. (2012)

^e Muligetla (2009)

^f RFA (2007)

^g Cho et al. (2012)

^h Marchetti et al. (2008)

ⁱ Marchetti and Errazu (2008)

^j Zhang et al. (2003)

^k Sakai et al. (2009)

^l Apostolakou et al. (2009)

^m Sotof et al. (2010)

ⁿ Haas et al. (2006)

^p You et al. (2008)

^{*} US\$/tonne

[#] US\$/liter

production capacities, palm biodiesel is found to be economically competitive (see Table 6.1).

The type of method used for the oil conversion into biodiesel is a major contributing factor to the overall production cost of the plant. For instance, a biodiesel plant using rapeseed oil as feedstock and using enzymes as catalysts was found to produce very expensive biodiesel (US\$1.15–2.04 per liter) (Apostolakou et al. 2009; Sotoft et al. 2010). Palm biodiesel produced using enzymes as catalysts in lower plant capacities have almost the same cost as that for rapeseed oil biodiesel produced under similar conditions but high plant capacities (see Table 6.1). This means that, scaling up palm biodiesel plants for enzyme-catalyzed processes would be cheap compared to rapeseed oil biodiesel produced using enzymes as catalysts.

An economic analysis performed on algal biodiesel production plant by Brian (2011) shows that an economically viable algae-to-biodiesel commercialization would largely depend on government subsidies and the future price of crude oil as well as optimized biomass yields. The results from the analysis showed that positive net present value (NPV) with reasonable rates of return would be possible only if moderately high yields of algal biodiesel and extremely high prices (>US\$100 per barrel) of fossil diesel are realized with substantial subsidies or tax breaks on renewable energy systems. For a low algal yield (67 tonne/ha), low subsidy (US\$0.50/gal), and low crude oil price (US\$74/barrel), net present value of US\$125.2 million was recorded. With a high oil yield (134 tonne/ha), high subsidy (US\$1.50/gal), and high crude oil price (US\$108/barrel), a higher NPV of US\$126.5 million was recorded. For a moderate oil yield (101 tonne/ha), moderate subsidy (US\$101/gal), and moderate crude oil price (US\$84/barrel), an NPV of US\$56.6 million was recorded. The lowest NPV (US\$2.5 million) occurs when there is moderate oil yield, high subsidy, and high crude oil price. This data indicates that, biodiesel production depends largely on subsidies and without these incentives, they become unsustainable.

Moreover, an economic analysis by Wiskerke (2008) on *Jatropha curcas* L. cultivation indicates that the total production cost for 1 kg of seeds is US\$0.10. His calculations also revealed a negative NPV of –US\$229/ha. Currently in Tanzania where *Jatropha curcas* L. is grown on commercial scale, a kilogram of jatropha seeds costs US\$0.26 (Messemaker 2008). Economic analysis carried out by Marchetti et al. (2008) on spent oil transesterification shows that 76–80 % of the operating cost is associated with the cost of raw material. Thus, the cost of *J. curcas* oil (US\$0.324 per liter) has a great impact on the profitability of the plant.

A low cost raw material and the use of heterogeneous catalyst can help improve increase productivity and sustainability of the production plant. Again, the conventional alkaline catalyzed transesterification is found to be the most economically sustainable means of producing low cost palm biodiesel.

Though palm biodiesel cost are generally found to be cheaper than fossil diesel, the initial investment needed is huge thus the need for incentives and subsidies policies to be implemented. For various subsidy scenarios for biodiesel production that were considered by Ong et al. (2012) in their work, they concluded that the final cost of palm biodiesel with subsidies of US\$0.10 and 0.18 per liter are

compatible and lower than fossil diesel when palm oil price is not more than US\$0.924 per liter. However, when the price of palm oil goes up to US\$1.056 per liter, it no more becomes competitive with fossil diesel because the biodiesel production price becomes higher than fossil diesel although a subsidy of US\$0.18 per liter is still provided.

Lozada et al. (2010) also concluded that palm biodiesel would be competitive with fossil diesel when there is value added tax (VAT) exemption and the government grants a fiscal incentive for palm biodiesel. Palm biodiesel production plant is again found to have better economic performance than jatropha and castor oil biodiesel in Africa due the high productivity of the oil palm (Mulugetta 2009).

6.2.3 Bioethanol Production from Oil Palm Fronds (OPF) Juice: Cost–Benefit Assessment

Bioethanol can be produced from OPF using either the juice (from the fresh OPF) or cellulose from the fibers (e.g., dried fronds) as feedstocks. Many authors (Goh et al. 2010; Fazilah et al. 2009) have used hydrothermal pretreatment and enzymatic hydrolysis for cellulosic ethanol production from OPF. On the other hand, these pretreatment methods for cellulosic ethanol production are costly because they involve the use of chemicals, high temperature and pressure. Extracting OPF juice for bioethanol do not need harsh treatments steps or chemicals hence a cost-effective and sustainable approach thus in this study, the juice from OPF is extracted and utilized for bioethanol. Cost benefit assessment of bioethanol from palm wastes like OPF, empty fruit bunches (EFB), oil palm trunk (OPT), etc., has not been reported.

6.2.3.1 Process Description and Economic Evaluation Method

In the plant, there are three OPF storage tanks with hoppers, which are transported to the juice extraction unit by means of conveyors. During the pretreatment stage, the OPF undergo size reduction by wet milling at room temperature. The OPF is then pressed to obtain an unrefined juice (about 97 % sugar recovery), which is further purified in using vibrating screen to remove fibers, particles, etc., that can affect the yield and quality of bioethanol produced. The juice is then sterilized in a two-stage heat exchangers (at temperature 90–95 °C using steam as exchange medium) in order to avoid contaminations and generation of unnecessary metabolites during the fermentation stage. The sugar in the juice is then hydrolyzed into glucose, which can then be easily assimilated by the microorganisms during fermentation (Quintero et al. 2008). It is assumed that after sterilization, the juice from the OPF has a concentration of about 25 wt %. The composition of OPF is given in Chap. 3 (Sect. 3.4.4) and the juice from OPF have also been analyzed by Zahari et al. (2012) to contain about 76.09 g/l total free sugars with glucose

Table 6.2 Annual resource inputs, outputs and discounted cash flow data for bioethanol production from OPF

Item	Unit	Value
Project life time	years	20
Plant capacity	tonnes	65,000
	OPF/year	
Discount rate	%	8
Financing	% equity	30
Plant depreciation	% declining balance	200
Plant recovery period	years	5
Corporation tax rate	%	25
Construction period	years	2.5
Startup time	months	2
<i>Energy and utilities</i>		
Electricity	GWh/year	25.96
Process water	m ³ /year	290.54
Labor	hr/year	100,573.54
<i>Chemicals/raw materials</i>		
Urea	tonnes/year	140.98
Yeast	tonnes/year	217.82
Phosphate	tonnes/year	143.88
<i>Products</i>		
Bioethanol	tonnes/year	14,400
OPF fibers (after juice extraction)	tonnes/year	28,778
Carbon dioxide	tonnes/year	13,766

content of 53.95 g/l juice. The sugars in the sterilized and hydrolyzed OPF juice are fermented (at 35 °C) using hexose-fermenting yeast (e.g., *Saccharomyces cerevisiae*) to produce bioethanol. In the fermenter (a jacketed stirred tank bioreactor), phosphate and urea solutions are added to the broth. About 95 g/l bioethanol can be produced from every 200 g/l of total sugars (Sánchez et al. 2010). The bioethanol from the fermenter was concentrated to about 91 wt% using strippers and a rectifier before purification to about 99.5 wt% using molecular sieves (to obtain fuel-grade ethanol) in order to break the ethanol–water azeotrope. The fibers and other solid wastes (co-products) left after the milling, extraction or filtration processes are dried in a rotary oven to about 12 % moisture and sold to the cogeneration plant in the palm oil mill.

Table 6.2 shows the annual inputs and outputs of the bioethanol production plant which formed the bases for the economic assessment in this study. An annual production capacity of 65,000 tonnes of OPF (to produce 14,400 tonnes of bioethanol annually) was assumed for the base case process and the plant is considered to operate 330 days per year. Literature data from Sánchez et al. (2010) and Humbird et al. (2011) were used for some of the economic assessment of OPF bioethanol.

For the economic assessment, the capital costs were estimated from the cost of individual equipment used in the plant using the Chilton method (Peters et al. 2003). The compilations of standard equipment like pumps, heat exchangers,

Table 6.3 Operating cost used in the estimation of palm bioethanol production cost

Item	Unit	Value
<i>Feedstock</i>		
OPF	US\$/kg	0.020
<i>Chemicals</i>		
Urea	US\$/kg	0.76
Yeast	US\$/kg	0.57
Phosphate	US\$/kg	1.05
<i>Energy and utilities</i>		
Electricity	US\$/kWh	0.06
Process water	US\$/tonne	0.36
<i>By-products credits</i>		
OPF fiber (after juice extraction)	US\$/kg	0.020
<i>Other cost</i>		
Labor	US\$/employee-yr	53,886
Maintenance	% FCI	2
Insurance	% FCI	1

Sources Chemical Market Report (2010); Kabir et al. (2010); Lohrasbi et al. (2010); Gomes (2011)

distillation columns, fermenters, tanks and vessels, etc., were obtained from Gerrard (2000) while material factors for stainless steel equipment were also obtained from Coulson et al. (1999). The vendor quotations for sophisticated equipment like filter presses, milling machines, molecular sieve column, etc., were obtained from Aden et al. (2002). The equipment shipping cost was assumed a negligible percentage of the capital cost of the equipment. Equipment, chemicals/raw materials, and labor costs were indexed to 2009 using Marshall and Swift cost index (Chemical Engineering 2010).

Working capital was 40 % of the fixed capital investment while the annual inflation and residual value were taken as 4 and 50 %, respectively (Brown 2007). Using the recommendations from Branan (2002) and Brown (2007), the equipment sizing was done based on material balancing. Bioethanol production cost were estimated using the ex-factory selling price of ethanol which makes the NPV of the production process equal to zero (Lohrasbi et al. 2010). Table 6.3 shows the operating costs for the economic assessment of the bioethanol production plant.

6.2.3.2 Economic Assessment Results

The summary of the economic evaluation of the bioethanol production plant is shown in Table 6.4. The capital investment for the plant is highly dependent on the type of feedstock, plant capacity, and economic conditions of the location of the plant. For a plant capacity of 14,400 tonnes of bioethanol per year, the fixed capital cost was estimated to be US\$57.68 million.

A sensitivity analysis was carried out to choose a suitable discounted cash flow rate of return to analyze the bioethanol production cost. The cost of utilities and

Table 6.4 Summary of economic analysis of OPF bioethanol

Item	Unit	Value	Description ^a
Equipment cost (EC)	Million US\$	24.85	–
Equipment installation cost	Million US\$	8.70	35 % of EC
Pipeline installation cost	Million US\$	14.91	60 % of EC
Instrumentation	Million US\$	2.49	10 % of EC
Electrical installations	Million US\$	0.33	–
Isolation	Million US\$	2.49	10 % of EC
Land cost	Million US\$	0.651	US\$48.44/m ²
Buildings	Million US\$	3.72	15 % of EC
Auxiliary services	Million US\$	6.21	25 % of EC
Total installed cost (TIC)	Million US\$	39.50	–
Project and site management	Million US\$	9.88	25 % of TIC
Contingencies	Million US\$	5.93	15 % of TIC
Other costs	Million US\$	2.37	6 % of TIC
Fixed capital investment	Million US\$	57.68	–

^a Descriptions were taken from Branan (2002) and Brown (2007)

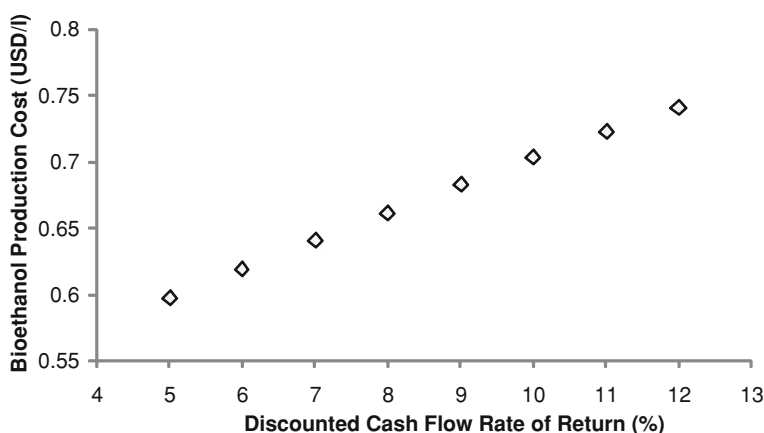


Fig. 6.2 Variation of bioethanol production cost with the discounted cash flow rate of return (Plant capacity 14,400 tonnes of bioethanol per year; OPF price of US\$0.020/kg)

labor were considered to be constant while the bioethanol production cost and feedstock costs were fixed at US\$0.70 per liter bioethanol (based on fixed capital investment and plant capacity) and US\$0.020 per kg OPF. Bioethanol costs were evaluated based on the method of discounted cash flow rate of return with values between 5 and 12 % as shown in Figure 6.2. A minimum bioethanol production cost of US\$0.662 per liter was obtained at a discounted cash flow rate of return of 8 % which is a little higher than those obtained for many other feedstocks like wheat, sugar beet, and cellulosic ethanol (see Table 6.5). Plant capacities above 43,000 tonnes per year was found to be the potential one for good investment.

Table 6.5 Comparison of bioethanol cost from different feedstocks

Feedstock	Bioethanol price (US\$/liter)	References
Sugar cane juice	0.48	Balat and Balat (2009)
Wheat	0.87	Balat and Balat (2009)
Sugar beet	0.87	Balat and Balat (2009)
Wheat straw	0.55	Littlewood et al. (2013)
Corn	1.03	Balat and Balat (2009)
Molasses	1.00	Quintero et al. (2012)
Sugarcane juice	0.75	Quintero et al. (2012)
OPF	0.70	This study

Cellulosic ethanol is found to have the highest price compared to the other types of biofuels. Most researches on economics of bioethanol production suggest the possibility of considerable spatial heterogeneity in the correct choice of feedstock for cellulosic ethanol production. Though the feedstocks for cellulosic ethanol may be extremely cheap, low ethanol yield would affect the economic viability of the plant (Perrin et al. 2008).

On the other hand, Gómez et al. (2011) have assessed biomethanol from oil palm wastes for economic feasibility. According to their results, a biomethanol production plant of capacity 193,000 tonnes per year located in Colombia, has a total production cost of US\$151.72 per tonne biomethanol (~US\$7.62 per GJ biomethanol). Comparing this value to biomethanol cost on the international market in 2010 (US\$339–832 per tonne biomethanol), it can be concluded that biomethanol production from oil palm biomass is economically feasible (Gómez et al. 2011) though there are more room for economic improvement of the plant.

6.2.4 Economic Sustainability Assessment of Biogas from Palm Oil Mill Effluent (POME)

Yeoh (2004) assessed the economic feasibility of producing biogas and electricity from the POME generated by a palm oil mill of production capacity of 45 tonnes palm fresh fruit bunches (FFB) per hour for 350 operating hours per month with annual capacity of 189,000 tonnes FFB. About 240–450 m³ per day of POME could be generated from the processing of this amount of FFB based on 25 working days per month. The anaerobic reactor was a stainless steel closed type while the biogas storage system comprised pressurized storage vessels, scrubbers, compressors, piping, and housing. For a 189,000 tonnes FFB processing plant for biogas generation, Yeoh (2004) estimated a capital cost of US\$609,050, annual operating cost of US\$95.950, annual cost benefit of US\$187.310, and payback time of 2.5 years based on 8 % interest rate and plant life of 15 years. He concluded that there is substantial annual rate of return on investment from the anaerobic treatment system with 58 % returns. However, with the generation of electricity from the biogas, the economic

benefits reduced but were still comparable to other heat generation systems. Pay back periods of 5–7 years were estimated for the integrated system for biogas and bioelectricity production from POME, which is normal with most biomass-based renewable energy systems for electricity generation Yeoh (2004) and Begum and Saad (2013). A return on investment of 3–6 % is a reasonable value showing that an integrated system for biogas and bioelectricity generation from POME is economically viable though there may be the need to improve the purity of methane produced during anaerobic digestion of POME.

Begum and Saad (2013) have also assessed the techno-economic feasibility of an integrated system which produces biogas and bioelectricity from POME generated from 30 tonnes of FFB per hour. They concluded that the plant is technically and economically feasible to operate as reported by Yeoh (2004). At chosen discount factors of 5, 10, and 15 %, the plant capacity of 30 tonne FFB/hr was found to be viable. However, plant capacities over 60 tonnes FFB/hr was found to be the potential one for investment. The payback period was 3.17 years when the capacity factor was 100 (Begum and Saad 2013).

6.3 Economic Impacts of Biofuels from Oil Palm Biomass and Improvement Options

Though it is always said that employers and employees of oil palm industries are rich, only about one-third have better living (Marti 2008; Colchester et al. 2006). The palm biofuel industry is a potential industry for rural development, job creation, and poverty alleviation (Hunt 2010; Schwarz 2010) but there may be other negative impacts on the society and the ecosystem at large. One main positive socio-economic impact of oil palm and palm biofuels production is the improvement that are realized in infrastructure establishment like schools, hospitals, religious centers, etc., which are easily accessible by the rural communities involved in the oil palm cultivation and processing. Income levels of these rural people are satisfactory due to fair compensations for transferred lands, regular income from plasma plantations, and other external income. Again, main roads leading to plantation communities are developed for facilitation of broad access to nearby markets hence increase in economic gains. The results from the survey of Andriani et al. (2011) in Indonesia show that the socio-economic impacts from palm biofuel production are more positive than environmental impact. Most smallholder families have benefited from high returns and incomes compared to their former livelihood activities (Rist et al. 2010). Other socio-economic benefits of palm biofuels include:

- Existence of an alternative source of energy, which is greener, compared to fossil fuels.
- Progress in research and development in finding alternative technologies for producing green energy through environmental, economic, and social sustainable ways (De Paula and Cristian 2009).

- Cost-effective biofuel compared to most biofuels produced from different feedstocks like rapeseed oil.
- Demand growth and improvement in developed countries due to emerging economies.
- Rationalized green energy utilization in industries, homes, etc., hence clean environment.

One other technical problem directly linked to the economic sustainability of palm biofuels is associated with palm oil yield. Though there are many efforts in increasing the oil yield by growers and palm oil researchers, the actual yields and the national productivity of the oil have stood still between 3.0 and 4.5 tonnes oil per hectare since the late 1990s (Tinker 2000; Rosediana 2009). However, about 8.6 tonnes oil/ha is possible using certain species (Henson 1990) though very difficult to achieve. Smallholders mostly have about 35–40 % lower yields compared to the private and government-owned palm companies (Rosediana 2009). These gap disparities in yield between private companies and smallholders may result from the differences in farming practices as well as the kind of input resources (that may be costly) into the cultivation and milling of the oil. With these challenges coupled with the escalating prices of inputs (like fertilizers) into palm oil production, the prices of palm oil keep rising though it remains the cheapest source of vegetable oil in the world.

Though palm oil and palm biofuels are better off in terms of cost compared to other biofuel types, oil palm growers and palm oil producers especially are not getting improved in their financial status. Mostly, the employees of private and public companies involved in the oil palm industry are well off compared to the rural people who are actually on the ground working. Over the past decade, research reports on oil palm and palm biofuel production have shown that the conditions of smallholders and workers are getting poorer and poorer (Wakker 2005; Colchester et al. 2006; Marti 2008). As reported by Colchester et al. (2006), over 92,000 people staying in an oil palm plantation community of population of about 504,000 are living in poverty and hunger with about 778 children malnourished. Figure 6.3 shows the socio-economic impacts of oil palm cultivation and palm oil milling in an Indonesian palm cultivation community. Figure 6.4 shows economic impacts of oil palm agriculture on landowners or customary users in Indonesia.

The highest socio-economic impact resulted from floods (68 %) followed by water pollution (65 %). Most communities in Indonesia are affected by floods after heavy rains and the clearing of forests and lands for oil palm cultivation may intensify this hence the high impacts from floods. The impacts from employment and easy access to good roads were 41 and 47 %, respectively. The impacts from resettlements and displacement of communities were low at 5 % probably due to supports given to the rural folks upon land transfers.

Generally, palm oil production as a preliminary yet vital stage of palm biofuel production is assessed to have positive economic impacts on the rural communities of Indonesia though there are significant negative impacts. Though some

researches have reported report that oil palm production could take away food cropland, in most rural communities where palm oil is cultivated, their access to food is appreciable with a positive impact of 76 % (Andriani et al. 2011). However, the quality of social networks of importance to livelihoods was very low. This means that oil palm production took away larger portions of the rural people's livelihood. Some memorable sites like gardens, etc., in the rural communities, which give them entertainments, were greatly affected.

There are many ways of improving the economic benefits of the oil palm industry for sustainable palm biofuel development. It is imperative to link and discuss economic issues pertaining to oil palm development with its environmental and social impacts in order to achieve sustainable development in the sector. As a way to improve the industry for sustainable palm biofuels production, enabling environment must be created within all the sectors of the industry. Areas with poor governance and weak institutions, which create economic barriers, must be improved for sustainability. Laws that govern land rights and overlapping institutional mandates between the central and regional governments, which create loose investment environment leading to high cost of establishing businesses, must be clearly outlined and implemented. Land allocations must be carried out in fair manner to avoid conflicts which would eventually lead to low economic lives.

In order to close the wide gap between private companies and smallholders' oil palm productivity, the private companies who have the financial resources and ability to address these issues should help the smallholders in this regard through appropriate training and technical supports. Again, smallholder must be funded in order to be certified for sustainable palm oil so that they can also have access to

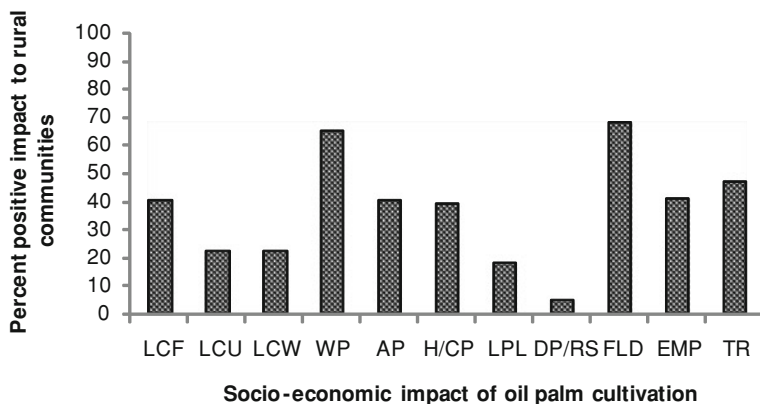


Fig. 6.3 Socio-economic Impacts of oil palm expansion in Indonesia. *LCF*—loss of customary access to forest products; *LCU*—loss of customary access to underutilized land for cropping; *LCW*—loss of customary access to water resources; *WP*—water pollution; *AP*—air pollution; *H/CP*—increased incidence of human or crop pest and diseases; *LPL*—loss of primary crop land; *DP/RS*—displacement/resettlement; *FLD*—flood; *EMP*—employment opportunities; *TR*—transportation and access to cities nearby (Andriani et al. 2011)

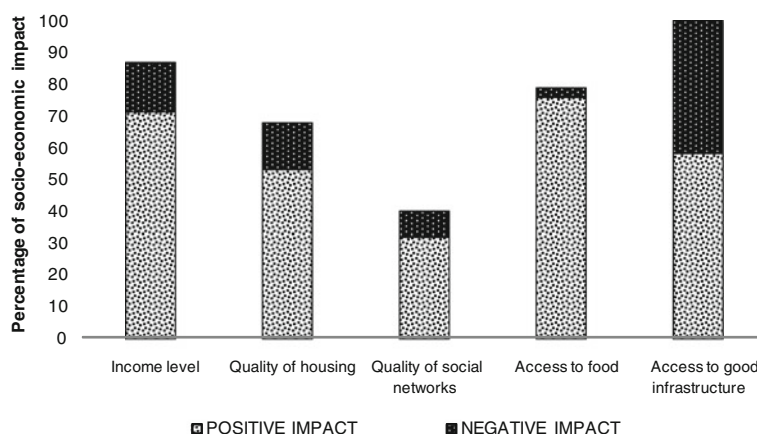


Fig. 6.4 Socio-economic impacts of palm oil production on landowners or customary users in rural communities of Indonesia (Andriani et al. 2011)

tools to implement best management practices to achieve sustainable palm oil development.

Again, the industry can be improved economically by expanding its downstream processing activities especially for palm oil milling. Most of the palm oil producing countries do not make proper economic use of the wastes (like PFAD, POME, PKC, etc.) generated during palm oil refining and FFB processing. The transformation of these wastes into value added bio-products would add employment opportunities to the industry hence increase in gross domestic product (GDP) (see Appendix G). For challenges associated with employments, more work could be done to identify major conditions which contribute positively to the number and quality of jobs created. Economic modeling is found to help predict how rural communities could embrace profit and bear the risks associated with oil palm cultivation, processing and palm biofuels production in order to help estimate the multiplier effect which can forecast job growth and improvement.

The development of biofuels from oil palm biomass carries with it many challenges and uncertainties regarding oil palm growers' stability, market prices, constant flow of feedstock, etc. The uncertain market prices of oil prices and lack of market outlets can make the profitability of biofuel dependent on volatile oil prices and plant location. Again, rapid innovation in production technology and new varieties of energy crops may result in uncertainties, which would affect biofuel investment decisions. Thus, there is the need for extensive research and development in biofuels advancement in order to accommodate the involving economic risks and uncertainties. Research is again important in implementing policies to support sustainable palm biofuel production in order to manage alternative methods of feedstock cultivation, insurance, safety mechanisms and other economic risks.

6.4 Conclusion

The economic sustainability of palm biofuels was assessed and compared with biofuels from other feedstocks. Palm biodiesel is found to be cost-competitive with fossil diesel even without policy subsidies but requires high initial capital investment for large capacity plants. Compared to biodiesel from tallow fat, rapeseed oil, soybean oil, etc., palm biodiesel is found to be cheaper for high capacity biodiesel production plants above 30,000 tonnes biodiesel per annum. Palm bioethanol (from OPF juice) is highly competitive to gasoline and bioethanol from other feedstock in terms of cost. Biogas production from POME for electricity generation has also been found to be economically sustainable. Though palm biofuels are found have positive economic impacts on the society, there are few other socio-economic issues which need to be improved for sustainable development. Improvement in management practices would reduce the negative impacts that palm biofuels have on the society for sustainable palm biofuels development.

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Chapter 7

Thermodynamic Sustainability Assessment of Biofuel Production from Oil Palm Biomass

Abstract In reality, all production processes proceed with the generation of entropy and destruction of useful energy of resource inputs. In view of this, the second law of thermodynamics can be directly linked with sustainability and sustainable development. Estimation of a system's exergy status in order to know the distribution of energy and matter, especially emissions, would help identify the efficiency of the system, hence improving it for sustainable development. In this chapter, the thermodynamic sustainability of biodiesel, bioethanol, biogas, and briquettes production from oil palm biomass are investigated via exergy analysis. Most studies on exergy analysis of biofuels production systems do not consider the production of the feedstocks though these stages are materials and energy intensive. The production of oil palm biomass for palm biofuels is assessed for thermodynamic feasibility in this study in order to give a complete overview of the contributions of every single unit within the palm biofuels production systems. Aspen Plus software was used for the mathematical modeling for all the case studies considered in this chapter. Potential causes and improvement options are also discussed in this chapter for sustainable palm biofuels production.

Keywords Thermodynamic sustainability • Palm biofuels • Oil palm biomass • Oil palm wastes • Biofuels exergy • Thermodynamic efficiency • Irreversibility • Palm biodiesel • Bioelectricity • Palm bioethanol • Exergy

7.1 Introduction

Energy is the driving force of almost all economies of the world thus, energy efficiency in production is important for sustainable development. The responsible production and consumption of biofuels must take into account issues of resource availability (exergy) and utilization, economic investment, and environmental impacts. Thermodynamic efficiency assessment combines both the economic and

environmental aspects of sustainability (Valero et al. 1986) to give a clearer view of how energy is utilized during a process. Thermodynamic sustainability assessment is carried out using tools like energy and exergy analyses. More advanced tools like thermoeconomic analysis, exergoeconomic analysis, exergetic life cycle assessment, etc., could be used to assess the thermodynamic sustainability of production systems. The simultaneous use of the first and second laws of thermodynamics is applied to describe the quality and quantity of energy as well as its depletion rate within a system (Bejan et al. 1996; Fiorini and Sciubba 2005). When a system is assessed in terms of thermodynamic sustainability, the primary causes of its inefficiencies and the cost of obtaining the system's internal flows are established in a more comprehensive manner (Ayres et al. 2007; De Swaan et al. 2004).

The thermodynamic sustainability assessment tool, exergy, has been beneficial to the new engineering paradigm shift toward sustainable bioenergy development. Exergy helps to articulate the amount of resources that is consumed in any industrial process by quantifying the exergy losses in each unit operation. Exergy is a measure of the ability to perform work and higher exergy efficiencies are attained for processes in which exergy is less destroyed.

Thermodynamic or exergy analysis has been applied to biofuels production systems for sustainability assessment. The production of biohydrogen from biomass (Abuadala et al. 2010), biodiesel from used cooking oil (Talens et al. 2010), biodiesel from palm oil (Jaimes et al. 2010), bioethanol from sugarcane bagasse (Ojeda et al. 2011), biogas from brewer's spent grain (BSG) (Martin and Parsapour 2012), dimethyl ether from biomass (Zhang et al. 2009), biomethanol from sewage sludge (Ptasinski et al. 2002), oil palm fronds pretreatment systems for bioethanol production (Ofori-Boateng and Lee 2013), etc., have been assessed in terms of thermodynamic sustainability via exergy analyses. These studies address irreversibilities as main causes of exergy loss due to high heat transfer across high temperature difference resulting from the use of high quality exergy resources such as fossil fuel. Thermodynamic properties of streams in biofuels production systems for exergy calculations have been easily attained with the help of computer aided software like Aspen Plus (Dhar and Kirtania 2009; Doherty et al. 2010; Pellegrini and Silvio de Oliveira 2007), HYSYS (West et al. 2008), etc.

The cultivation of oil palm, palm oil milling, and conversion of palm biomass into biofuels make use of high-energy content resources like fossil fuel, which could affect the thermodynamic sustainability of the system. Though palm oil is the most consumed vegetable oil in the world today, its production processes have not been assessed in terms of exergy in order to improve yield and make it more economical. Because palm oil is the cheapest source of vegetable oil, it is gradually becoming one of the high biofuel feedstock alternatives. This chapter focuses on the degree of exergy destruction in palm biofuels production systems in order to assess their thermodynamic efficiencies for sustainable development. Process improvement options are also elaborated in this chapter.

7.2 Energy, Entropy, and Exergy: Comparative Overview

According to the first law of thermodynamics, energy can neither be created nor destroyed but conserved for all processes. This actually means that energy can never be consumed in a process which in fact is not logical considering irreversible processes in real situations. For instance, during heat transfer between a medium and its surrounding, there comes a specific time where the medium reaches the dead state,¹ where there is no extra heat exchange because the exergy content by then has been completely destroyed but no energy has been consumed.² At the dead state, the conditions of mechanical (the pressure), thermal (temperature), and chemical (chemical potentials) equilibria between the system and the environment are satisfied (Utlu and Hepbasli 2007). Because the conditions of the system are equal to those of the environment, the system has no motion or elevation relative to coordinates in the environment. Under these conditions, there is neither possibility of a spontaneous change within the system or the environment nor an interaction between them. The amount of resource that enters a process does not come out the same due to entropy generations within the system that has caused certain part of the resource to be consumed. Exergy is the quantity that can be consumed in processes and not energy hence, energy analysis though helpful may not actually quantify the quality of resource available to perform work which in fact, exergy analysis does. Sustainability emphasizes more on resource quality hence the need to quantify resources in terms of exergy in order to ascertain the degradation rate during a production process.

Energy as a physical quantity is dependent on only the characteristics of matter or energy flows but independent of environmental properties. This implies that energy balance does not quantify the usefulness or quality of a resource or provide information on resource destruction in a process (Sorguven and Ozilgen 2010). However, exergy analysis combines the first and second laws of thermodynamics to quantify the useful portion of energy that produces work (Peralta et al. 2010). Exergy of a resource is that part of the available energy which is fully convertible to other forms of energy.

Exergy can also be defined as the maximum theoretical useful work obtainable when a system is brought into thermodynamic equilibrium with its surrounding whereby there exist interactions between the system and environment (Wall 2010; Sciubba and Wall 2007).

Exergy analysis is also a thermodynamic sustainability tool that can be applied in quantifying emissions and wastes streams from a process (De Meester et al. 2006; Hermann 2006) as it is always measured based on a reference environment.

¹ In a dead state system, the exergy of the stream or system is always zero due to the attainment of equilibrium with the reference environment (Ahrendts 1980).

² This makes the use of the phrase 'energy consumption' so ambiguous in that energy can never be destroyed according to the first law of thermodynamics. What is actually consumed is exergy hence, 'exergy consumption.'

In a system where the work efficiencies of biofuels and their production systems are compared to fossil fuels, exergy analysis presents a better assessment tool in identifying their ‘exergy efficiencies’ and impacts on the environment (Talens et al. 2007; Ptasiński et al. 2007; Peralta et al. 2010).

Exergy quantifies the effect of energy and matter dissipation (entropy) while entropy quantifies the state of dispersion, i.e., the degree to which energy and matter are dispersed in a process which is nonideal or irreversible (Dewar 2005; Olawale and Adefila 1998).

7.3 Components of Exergy

Exergy may have components like physical (Ex_{ph}), chemical (Ex_{ch}), kinetic ($c^2/2$),³ potential (gx),⁴ and nuclear (Ex_{nu}) exergies depending on the type of system under consideration (Szargut 2005; Carnot 1978; Kotas 1985). For instance, in a system which involves heat, work, and material transfers, the kinetic, potential, and nuclear exergies are not accounted for.

The *physical* or *thermo-mechanical* exergy of a system consists of mechanical exergy which depends on the system’s pressure; and thermal exergy which also depends on the system’s temperature (Carnot 1978; Szargut et al. 1988). According to Szargut et al. (1988), Eq. (7.1) mathematically defines physical exergy as:

$$Ex_{ph} = (H - H_0) - T_0(S - S_0) \quad (7.1)$$

where $(H - H_0)$ and $(S - S_0)$ are the enthalpy change and entropy change of the system, respectively, at an environmental temperature of T_0 (298.15 K) and pressure P_0 (1 atm). The physical exergy of a system varies mathematically depending on the type of interactions occurring in the system. Equations 7.2 and 7.3 mathematically represent physical exergies of a perfect gas system (with constant specific isobaric heat capacity); and perfect solid and liquid systems (with constant specific heat capacity), respectively (Szargut et al. 1988):

$$Ex_{ph} = c_p \left\{ (T - T_0) - T_0 \ln \frac{T}{T_0} \right\} + RT_0 \ln \frac{P}{P_0} \quad (7.2)$$

$$Ex_{ph} = \left\{ (T - T_0) - T_0 \ln \frac{T}{T_0} \right\} - v_m(P - P_0) \quad (7.3)$$

where Ex_{ph} is the physical exergy, c_p is the specific heat capacity, v_m is the specific volume at temperature T_0 (298.15 K), T is the temperature of the system, R is the

³ c is the velocity relative to Earth’s surface.

⁴ g is the constant of gravitational acceleration and x is the height.

gas constant (8.314 4621 J/mol/K), P is the system's operating pressure, and P_0 is the initial pressure (1 atm).

Chemical exergy is the maximum net useful work obtained when a pure substance or working fluid into complete thermodynamic equilibrium with its environment of known chemical composition upon interactions in a system (Szargut et al. 1988). The chemical exergy of a material stream is the difference in the chemical potentials of the pure process components and the reference environment components in their environmental concentrations at their environmental conditions ($T_0 = 298.15$ K, $P_0 = 1$ atm) (Sato 2004). Chemical exergy is the most important exergy contribution to the overall exergy value of most natural resources like palm fruits. Equation 7.4 defines chemical exergy mathematically as:

$$\text{Ex}_{\text{ch},i} = \Delta G_f^o + \sum_k N_k \text{Ex}_{\text{ch},k}^0 \quad (7.4)$$

where $\text{Ex}_{\text{ch},i}$, N_k , ΔG_f^o , and $\text{Ex}_{\text{ch},k}^0$ represent chemical exergy, number of moles of the k th reference species, Gibb's free energy of formation of the reference reaction, and the standard chemical exergy of the k th reference species, respectively.

The exergy of a steam is therefore found from Eq. 7.5:

$$\text{Ex}_{\text{system}} = \text{Ex}_{\text{ch}} + \text{Ex}_{\text{ph}} + \text{Ex}_{\Delta\text{mix}} \quad (7.5)$$

where $\text{Ex}_{\Delta\text{mix}}$ is the exergy of mixing of the system also mathematically defined by Eq. 7.6 (Szargut et al. 1988; Ayres and Ayres 1998):

$$\text{Ex}_{\Delta\text{mix}} = H_{\Delta\text{mix}} - T_0 S_{\Delta\text{mix}}[T, P] \quad (7.6)$$

where $H_{\Delta\text{mix}}$ is the enthalpy of mixing.

In this chapter, the exergy of mixing is assumed to be part of the physical exergy.

7.3.1 Exergy Destruction and Exergy Efficiency

Due to chemical reactions and other physical interactions between molecules in a system,⁵ real processes are irreversible (Rivero 2002; Wall 2010) and some part of the total exergy of the interacting resources degrade during the process. This degradation results in low exergy output compared to the input exergy. This destroyed exergy due to entropy generation is often referred to as the *internal or endogenous exergy destruction* (Rivero et al. 1999; Rucker and Gruhn 1999). Irreversibility in a system is caused by lack of thermodynamic equilibrium and the dissipative effects associated with a natural process which leads to entropy

⁵ Examples of interactions in a system which lead to irreversibilities are heat and momentum transfers through a finite temperature difference, mixing of matter at different compositions or states, unrestrained expansion, and friction.

generation and process inefficiencies. The exergy destroyed due to entropy generation in a system is unavoidable but can be minimized to some extent through various means which are discussed in this chapter. In energy conversion systems like biofuels production, the extent of exergy destruction is caused by equipment inefficiencies and energy value of resources entering the system. The endogenous exergy destruction of a system does not depend on the changes in the exergy destruction within the remaining components hence it gives accuracy to the performance of the system (Tsatsaronis et al. 2006).

On the other hand, *external or exogenous exergy destruction* results from the wastes and emissions that are released into the environment without treatment (Tsatsaronis et al. 2006). Exergy analysis based on only exogenous exergy of the system cannot exclusively justify the efficiency of the system. The sum of internal and external exergy destructions gives the total exergy destruction. Energy analysis cannot quantify the amount of degraded useful work a resource carries thus, the need for exergy analysis which is able to detect locations within the process which may need improvements (Rosen and Dincer 1997).

Mathematically, exergy destruction is defined by Eq. 7.7 and can further be expanded into Eq. 7.8 (Ayres and Ayres 1998; Cornelisse 1997):

$$\sum \text{Ex}_{\text{heat}} - \sum \text{Ex}_{\text{work}} + \sum \text{Ex}_{\text{mass,in}} - \sum \text{Ex}_{\text{mass,out}} = \text{Ex}_{\text{destruction}} \\ = T_0 S_{\text{generation}} = I \quad (7.7)$$

$$\sum \left(1 - \frac{T_0}{T} \right) - W + \left(\sum_i m_i \text{Ex}_i \right)_{\text{in}} - \left(\sum_i m_i \text{Ex}_i \right)_{\text{out}} = \text{Ex}_{\text{destroyed}} \\ = T_0 S_{\text{generation}} = I \quad (7.8)$$

where Ex_{heat} , Ex_{work} , $\text{Ex}_{\text{mass,in}}$ and $\text{Ex}_{\text{mass,out}}$ represent the exergy destruction due to heat, work, mass inputs, and mass outputs, respectively. $\text{Ex}_{\text{destruction}}$, $S_{\text{generation}}$, m_i and Ex_i represent exergy destruction, entropy generation, mass of resource/stream, and exergy of resource/stream, respectively. $W = \text{Work}$, $\text{Ex}_i = \text{exergy of } i\text{th component}$, $m_i = \text{mass of } i\text{th component}$, $I = \text{irreversibility}$, T and T_0 are the temperature of the stream/resource, and environmental/reference temperature (298.15 K).

Exergetic efficiency is defined as the ratio of the total exergy flow output to the total exergy flow input and can be expressed mathematically by Eq. 7.9 (Rivero et al. 1999):

$$\text{Ex}_{\text{efficiency}} = \frac{\text{Ex}_{\text{flow-out}}}{\text{Ex}_{\text{flow-in}}} \quad (7.9)$$

The exergy efficiency is a measure of a system's ability to transform raw materials into useful products. For a thermodynamically sustainable system, the exergy efficiency must be nearer to 1 or 100 %. Production systems are considered thermodynamically unsustainable if large amounts of exergy resources are consumed compared to that produced as useful products (Wall 2010). The reduction of exergy losses during a process shifts it to a more exergetic efficient system

whereby the conversion performance of the system is improved and the generation of wastes and emissions from the system are reduced.

7.4 Methodology for Exergy Analysis of Biofuels Production from Oil Palm Biomass

In this chapter, the methodology adopted to assess the thermodynamic feasibility of biofuels production from oil palm biomass follows the order:

- System boundary and functional unit definitions.
- Materials and energy flow balance for unit operations within the production systems.
- Chemical exergy calculations for individual streams.
- Physical Exergy calculations for individual streams with the help of Aspen Plus software.
- Exergy balance calculations for each unit operation within the production system.
- Determination of exergy destruction and exergy efficiencies for the production systems.

Almost all the current researches on exergy analysis of biofuels have concentrated only on the units for feedstocks conversion without consideration of the cultivation units. However, this chapter focuses on full exergy analysis of palm biofuels from feedstock extraction to biofuel production. In this chapter, biofuels like biodiesel from crude palm oil (CPO), biodiesel from palm fatty acid distillate (PFAD), bio-oil from empty fruit bunches (EFB), bioethanol from oil palm fronds (OPF), biogas from palm oil mill effluent (POME), and pelletized fuel from oil palm trunks (OPT) are assessed for thermodynamic sustainability.

In this chapter, the production of machinery, equipment, chemicals as well as the construction of all infrastructures like buildings were not included in the system boundary. The reason for these exclusions is that this study did not consider cumulative exergy consumption (CExC) values which considers the production of all the input resources [except the production of palm fresh fruit bunches (FFB)]. Diesel fuels used in transportation are also not included except the use of fuels to convey raw materials, etc., to unit operations within the production plants.

Control of emissions from harvesters and other agricultural machines are not included in the system boundary. They are also considered as part of the waste streams in the plant.

The chemical exergy for each pure substance, organic, and utilities was calculated using their standard chemical exergies ($Ex_{ch,i}^0$) from the literature (Szargut 1989; Ayres and Ayres 1998; Rivero and Garfias 2006) using Eq. 7.10:

$$Ex_{ch,i} = \Delta G_f^0 + \sum_i v_i Ex_{ch,i}^0 \quad (7.10)$$

where $Ex_{ch,i}$ = chemical exergy of substance, ΔG_f^0 = standard Gibbs free energy of formation, $Ex_{ch,i}^0$ = standard chemical exergy of component i , v_i = mole ratio of the i th component.

The environmental conditions chosen are $T_0 = 298.15$ K and $P_0 = 101.325$ kPa, which are equal to those for thermodynamic standard states, thus the standard chemical exergy is taken to be the same as the chemical exergy of all the species, i.e., $Ex_{ch,i}^0 = Ex_{ch,i}$.

The standard chemical exergy of complex chemicals that are not listed by Szargut et al. (1988) can be estimated by using the group contribution method (Shieh and Fan 1983) based on information about their molecular structure in determining the absolute entropy and enthalpy of formation values at standard conditions. This method has been used for the exergy calculations of pesticides and packaging materials (Schenk 2001). The Gibbs energy of formation can also be estimated directly for organic compounds, gases, and liquids with the method developed by Krevelen and Chermin (1952). It can also be found using the element method in which the chemical exergy is calculated by using the sum of the products of the stoichiometric coefficients of the elements in the formation reaction and the exergy values of the elements, and the Gibbs energy of formation values at the same standard temperature and pressure (Reid et al. 1977).

The total exergy of utilities such as steam, solar radiation, electricity, etc., were calculated using energy balance results from both production processes. The chemical exergy of steam was calculated using the standard chemical exergies of hydrogen and oxygen for the formation of water. Electricity exergy is taken as 1 MJ which is the same as its power value. Equation 7.11 estimates the exergy of solar radiation (Talens et al. 2010):

$$Ex_{solar\_radiation} = \text{Surface\_Area (km}^2\text{)} \times \text{Solar\_Radiation (MJ/m}^2\text{ year)} \times \beta \quad (7.11)$$

β value for biomass (i.e., 1.15) is obtained from the literature (Jørgensen and Svirezhev 2004) for oil palm seedlings and FFB production for 2 years.

Based on the mass and energy balance calculations, the process was simulated to obtain thermodynamic or physical properties of each stream. The physical exergy of each stream is, therefore, calculated using Eq. 7.1.

Since work is considered a pure exergy, the work value given by Aspen Plus can be used directly as the exergy due to work interactions within that stream. A positive work/heat/mass stream sign identifies an entry stream (consumption) while a negative sign of work/heat/mass identify exiting stream (generation) of an equipment within the process. For the purpose of consistency and clear explanation of results, all entering and exiting streams are assigned positive values. Two performance parameters namely exergy destruction and exergy efficiency are determined for all biofuels production systems in this chapter. The exergy destructions are calculated based on both the internal and external exergy destructions described by Rivero et al. (1999).

The internal exergy destruction is calculated by deducting the total exergy output (Ex_{out}) from the total exergy input (Ex_{in}) for every single unit operation as shown by Gouy-Stodola theorem in Eq. 7.12:

$$Ex_{dest-internal} = \sum Ex_{in} - \sum Ex_{out} = T_0 \Delta S \quad (7.12)$$

where $Ex_{dest-internal}$, Ex_{in} , Ex_{out} , ΔS and T_0 represent internal exergy destruction, exergy of mass flow in, exergy of mass flow out, entropy change ($S - S_0$), and environmental temperature (298.15 K), respectively.

The external exergy destruction is equal to the sum of the exergy of all waste streams in the production process as shown in Eq. 7.13:

$$Ex_{dest-external} = \sum Ex_{waste-to-environment} \quad (7.13)$$

where $Ex_{dest-external}$ and $Ex_{waste-to-environment}$ represent external exergy destruction and exergy of wastes released into the environment, respectively.

Hence, the total exergy destruction is found by adding the internal and external exergy destructions as shown in Eq. 7.14:

$$Ex_{dest-total} = Ex_{dest-internal} + Ex_{dest-external} \quad (7.14)$$

Aspen Plus software is a process modeling tool for steady-state simulation, design, performance monitoring, optimization, and business planning for chemicals, specialty chemicals, petrochemicals, and metallurgy industries (Aspen Tech 1988). Aspen Plus software (Aspen Tech 2004) has a databank of physical properties for most of the pure, organic, and inorganic substances. Throughout the studies, for systems involving vapor–liquid components such as methanol and glycerol, the NRTL model was used to predict the activity coefficients of the components in the liquid phase (Prausnitz et al. 1980). NRTL model is developed to capture the local concentration gradient between the molecule of interest and the surrounding media. This scenario creates an interaction energy difference among the involved molecules (Prausnitz et al. 1999).

Regardless of the thermodynamic option set used in the simulation of a process with Aspen Plus, enthalpy and entropy values at reference conditions are evaluated Rivero et al. (1999). Physical exergy can therefore be calculated manually using Eq. 7.1 with the thermodynamic results (enthalpy and entropy values) generated by Aspen Plus.

7.4.1 Exergy Analysis of Oil Palm Cultivation

The practices involved in the cultivation of oil palm are discussed in detail in Chap. 3 (Sect. 3.3). In the plantation unit, apart from the FFB obtained as the main product, OPF, OPL, and OPT are considered valuable products which can be transformed into other palm biofuels. OPT is mostly available during replanting of

new oil palm seedlings; thus in this study, OPF is considered the significant palm biomass as output resource from the palm cultivation system. Energy contributions from manual harvesting, field maintenance, etc., are converted into energy quantities (MJ) and included in the system boundary. A functional unit of 1 ton palm FFB is chosen. Some assumptions made in this study include:

- 1 ha of oil palm cultivated land produces 35 tons FFB.
- 0.13 kg oil palm seeds produce 0.69 kg oil palm seedlings.
- 1 ton of FFB produced generates 359.0 kg OPF (including OPL).

From normalized published research (Schmidt 2007; Yusoff 2006; Halimah et al. 2012; Nikander 2008) for oil palm nursery and plantation, 1,000 kg FFB requires 0.66 kg of palm seeds with fertilizer and pesticides applications for two years. The nursery is irrigated manually while a pump driven by fossil fuel does the plantation system's irrigation. Harvesting, field establishment, and maintenance are carried out manually with appropriate tools. The direct energy use per hectare of farming land in the whole farming processes are calculated with Eq. 7.15 for mechanized cropping system (Bockari-Gevao et al. 2005):

$$ED = h \times AFU \times PEU \times RU \quad (7.15)$$

where

h	specific working hours per run (h/ha)
ED	specific direct energy use (fuel) for field operation (MJ/ha)
AFU	average fuel use per working hour (l/h)
PEU	specific energy value per liter of fuel (MJ/l)
RU	runs (number of applications in the considered field operation)

The labor energy input (MJ/ha) at every stage in the production system was estimated by Eq. 7.16 (Bockari-Gevao et al. 2005):

$$LABEN = \frac{LABOUR \times TIME}{AREA} \times LABENF \quad (7.16)$$

where

LABEN	labor energy (MJ/ha)
LABOR	number of working laborers
TIME	operating time (h)
AREA	operating area (ha)
LABENF	labor energy factor (MJ/h).

Oil palm cultivation system was not in complete material balance due to the continuous farming which may last for years. Since the structure of oil palm biomass is not well-defined, the thermodynamic properties are not exactly known. For instance, assuming the composition of the biomass to be $C_{\alpha}H_{\beta}O_{\gamma}N_{\delta}S_{\epsilon}$, then based on the biomass combustion heat of reaction, the enthalpy change of formation, ΔH_f^0

value of the biomass can be calculated where α , β , γ , δ , and ε are the mole contents of the elements C, H, O, N, and S, respectively, obtained from the ultimate analysis of the biomass (Jørgensen and Svirezhev 2004). Figure 7.1 summarizes the materials, energy, and exergy balances for oil palm cultivation system.

For about 59,573 MJ exergy of materials that entered the FFB cultivation system, about 48,424 MJ came out as exergy of the main products. This implies that about 11,145 MJ of exergy was destroyed for the production of 1 ton FFB. The overall exergy efficiency of the cultivation system is about 81.3 % with about 0.74 % being the exergy of wastes (polythene bags used for nursery). However, the nursery unit recorded about 34 % exergy efficiency with about 315 MJ exergy destroyed. Though the exergy destroyed in the FFB production system was higher (10,750 MJ) than that for the nursery system, it was more exergetically efficient. The main products from the nursery unit were oil palm seedlings and polyethene bags (wastes) which had low exergy contents compared to those of the input resources. This scenario always renders a system exergetically inefficient. In the FFB production unit, FFB and OPF were the main products whose exergy contents were high and closer to those of the inputs hence small amount of exergy destroyed. The exergy content of the main input into the cultivation system (i.e., oil palm seeds) was upgraded from 13.8 to 40,463 MJ (for FFB). The cultivation of 1 ton of FFB can be considered exergetically efficient since its efficiency is near 1 (0.81). Scaling up of this system may reduce the exergy destruction drastically as large quantities of FFB with high exergy contents would be generated as the main product. Another reason for increased exergy destruction in the cultivation system is the dissipative effects of the light source (solar radiation) and the use of fossil fuel which eventually contributed to entropy generation hence exergy destruction in the cultivation unit. Exergy destruction can be minimized though the conversion of wastes into value-added bioproducts. Again, the amounts of input resources like fertilizers, pesticides, etc., could be reduced as they also contain high exergy content.

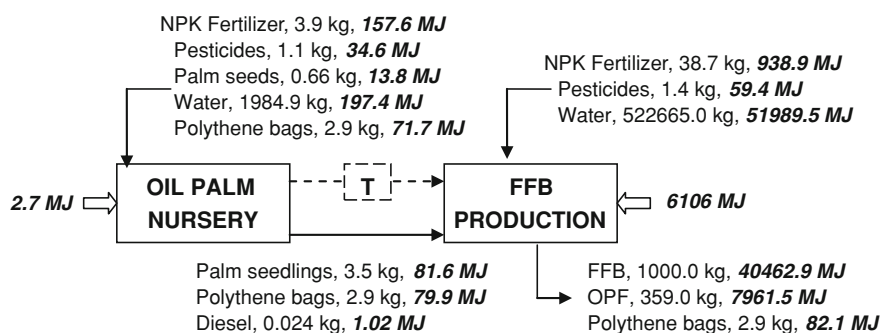


Fig. 7.1 Exergy balance for oil palm cultivation

7.4.2 Exergy Analysis of Palm Oil Milling Processes

Chapter 4 (Sect. 4.2.2) discusses the details of the main operations involved in the extraction of CPO from FFB. For 1 ton of FFB processed, about 140, 139.5, and 104 kg of steam are used by the sterilizer, stripper, and digger, respectively. A functional unit of 1 ton CPO is chosen for this section, thus 4,436 kg of FFB is processed to produce 1,145 kg of EFB, 763 kg of PPF, and 695 kg of palm kernel nuts (PKN). The standard chemical exergies for the input and output resources for the palm oil milling unit are shown in Table 7.2. The chemical exergies of FFB, EFB, PKN, PPF, CPO, and all wastes were calculated based on their chemical compositions. Process conditions were obtained from published reports (Ofori-Boateng et al. 2012a; Jaimes et al. 2010). Figure 7.2 summarizes the exergy balance for the production of 1 ton CPO from FFB.

Of about 189,374 MJ exergy of resources that entered the plant, only about 110,647 MJ was available to perform work. This implies that for a production of 1 ton CPO, about 78,727 MJ of exergy is destroyed (internal exergy destruction) representing about 41.6 % of the total exergy of resources that entered the plant as inputs. In the CPO milling unit, about 822 MJ of exergy was generated as wastes (external exergy destruction) representing about 0.43 % of the input exergy. Thus, the total exergy destroyed during the production of 1 ton CPO is about 79,549 MJ. The overall exergy efficiency of the CPO milling unit was about 58.4 %. The exergy of FFB (187,692 MJ) that entered the mill for 1 ton CPO production was drastically reduced to about 110,647 MJ useful product that could produce work. This means that FFB was degraded (i.e., about 59 % of FFB exergy was destroyed) in course of the processes to obtain CPO, PPF, EFB, and PKN. In this study, EFB, PPF, and PKN that were generated as co-products were considered useful products. However, in a circumstance where they are regarded as wastes, the exergy destruction would be as high as 151,386 MJ representing about 80 % of the total exergy content of input resources. This situation would have reduced the exergy efficiency of the whole system to about 20 % (main contribution from external exergy destruction). Thus, the conversion of oil palm biomass like EFB, PPF, and PKN would improve the thermodynamic sustainability of the mill. In most palm oil mills, parts of the PPF and palm kernel shells (PKS) are utilized as boiler fuels for steam and bioelectricity production. EFB presently do not have any commercial use but are rarely digested together with POME to produce biogas of which the slurry is used as biofertilizer in the plantation. However, considering the unit operations individually, the purification and drying of CPO to remove excess water was the most exergetically efficient at 98.6 % with little internal exergy destruction of about 556 MJ. This means that only about 1.4 % of the total exergy inputs were destroyed to obtain CPO from this unit. Water, with very small exergy content (0.049 MJ/kg) was the main component in the entering steam of the purifier/dryer, which needed to be removed. The entering exergy was almost the same as the exiting exergy due to the insignificant exergy content of water hence low internal exergy destruction.

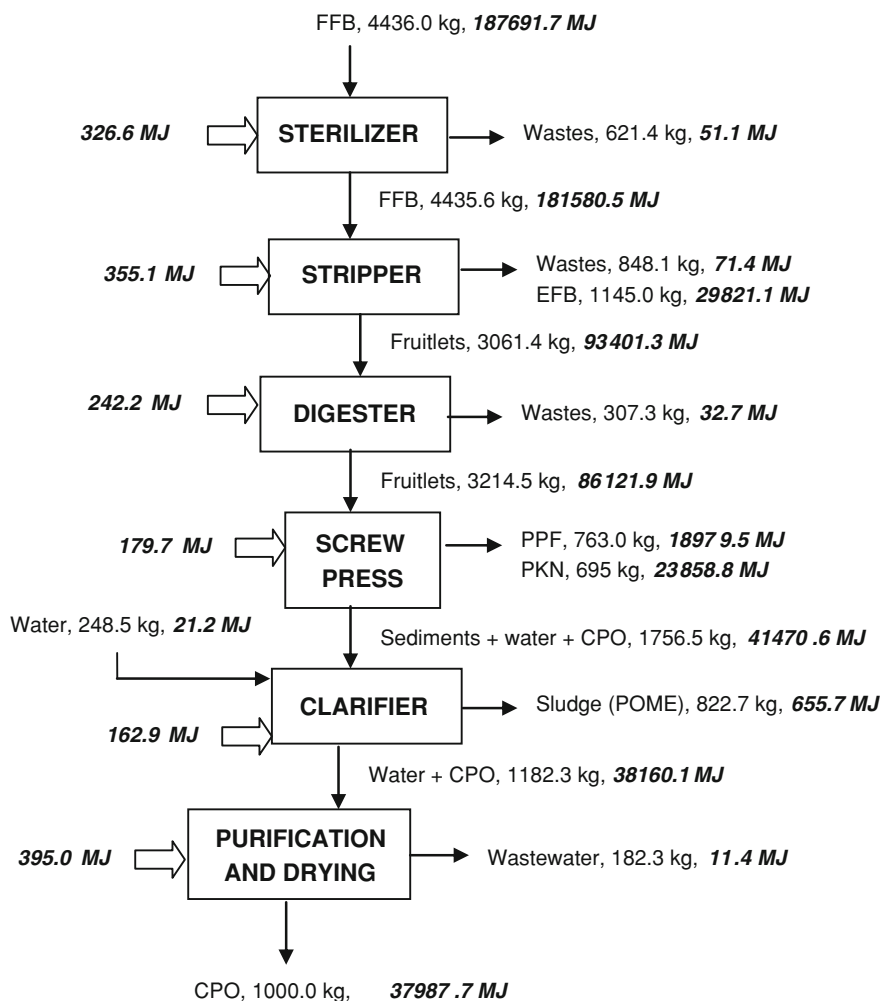


Fig. 7.2 Exergy balance for crude palm oil milling processes

The stripper recorded the highest exergy destruction of about 58,642 MJ which was about 32 % of the total exergy inputs. The stripper used high amounts of exergy from fossil fuels which could have increased entropy generation resulting from dissipative effects from fossil fuel use. Again, input exergy from FFB was high and it eventually reduced after the stripping process as seen from Fig. 7.2. If renewable energy is used during the process, it could increase the exergetic efficiency of the stripper. The exergy of wastes from the stripper is not high to affect the exergy efficiency significantly. However, it could be treated and recycled to be used in other unit operations (for instance in the clarifier where water is used) for improved processes in terms of exergy.

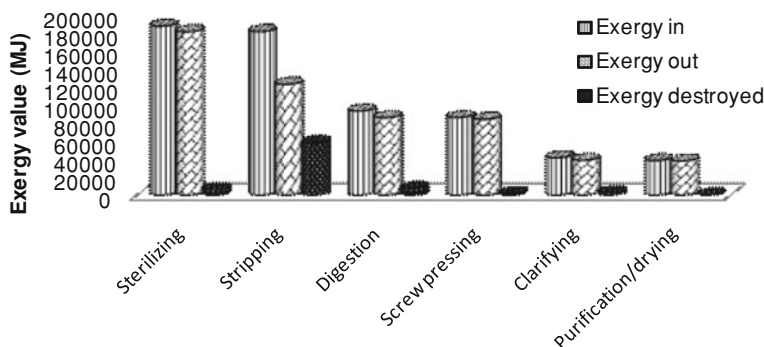


Fig. 7.3 Exergy balance of 1 ton CPO production system

The sterilizer, digester, screw press, and clarifier recorded exergy efficiencies of about 96.6, 92.0, 97.7, and 93.2 %, respectively. These unit operations were highly exergetically efficient though fossil fuels were utilized in the processes. However, the entering resources contained higher exergy than the outputs while the exergy of wastes was also insignificant. The individual subsystems can be considered thermodynamically efficient but the intermediate products like fruitlets which possibly rendered them efficient are not useful unless they are processed into CPO. Thus for the whole milling process, FFB conversion into CPO was not thermodynamically efficient neglecting all the intermediate products. The system could be improved thermodynamically by treating all wastes for recycling within the plant as well as utilizing some co-products for energy production to be utilized by the unit operations. Figure 7.3 shows the distribution of exergy in the unit operations within the palm oil mill.

7.4.3 Exergy Analysis of Biodiesel Production from Crude Palm Oil

CPO, according to this work, is assumed to largely contain the triglycerides C16:0 (palmitic acid, 38.5 %), C18:1 (oleic acid, 37.0 %), C18:3 (Linoleic acid, 8.0 %), and C18:0 (Stearic acid, 4.5 %). In the biodiesel production unit, esterification of CPO with methanol and phosphoric acid (H_3PO_4) is first carried out in a reactor in order to remove the free fatty acid (FFA) from the oil before transesterification. The CPO is then purified in which methanol is recovered simultaneously. In the methanol recovery unit, a ten-ideal stage with total condenser, kettle reboiler, and a 2.5 reflux ratio were used to remove approximately 99 % of the methanol in the CPO stream. Eight ideal stages with total condenser, kettle reboiler, and a 1.5 reflux ratio were used to separate the biodiesel from excess water. It was reported

Table 7.1 Chemical exergy calculations for crude palm oil (CPO)

Component	Standard chemical exergy (MJ/kg)	Mass (kg)	Chemical exergy (MJ)
Triglycerides	38.01	792.15	30,109.62
Free fatty acid	32.22	188.81	6,063.16
Water	0.049	8.55	0.42
Organic matter	16.65	5.49	91.41
Total exergy			36,264.61

Chemical exergy data obtained from Talens et al. (2010)

by Gómez-Castro et al. (2010) that column ideal stage between 9 and 15 is recommended for separation of water and methanol in biodiesel production.

Base-catalyzed transesterification with sodium hydroxide (NaOH) is carried out to convert the CPO into biodiesel and glycerol. The optimum reaction temperature used was 70 °C at 1 bar. About 96.7 % of the triglycerides that enters the transesterification reactor was assumed to be transformed into biodiesel in this study. The methyl ester phase containing glycerides, methyl esters (biodiesel), and methanol was then fed into a water washer at 50 °C in order to purify the biodiesel. Process conditions for this study were chosen based on pilot production data (Choo et al. 2011) and published research data (de Almeida et al. 2002; Ofori-Boateng et al. 2012b, c). A functional unit of 1 ton biodiesel is chosen for this study.

Chemical exergy is calculated using the total mass and chemical composition of the substance of interest together with the specific or standard chemical exergy which is obtained from Szargut et al. (1988). Table 7.1 shows a sample chemical exergy calculations for CPO

Table 7.2 shows the standard chemical exergies for the major input and output resources for the production of biodiesel from CPO. Figure 7.4 shows the exergy balance for biodiesel production from CPO.

Therefore for a kilogram of crude palm oil, $Ex_{ch,i}^0$ (CPO) = 36,264.61/1,000 = 36.26 MJ/kg

In order to produce 1 ton of biodiesel from CPO, about 995 kg of CPO was charged into the biodiesel production unit consisting of esterification and transesterification reactors as well as separation and purification units. CPO was degraded in terms of exergy during the process to form biodiesel. For about 39,524 MJ exergy of CPO that entered the biodiesel production system, about 3,004 MJ exergy was destroyed in order to obtain the palm biodiesel with exergy content of 36,520 MJ. For the whole production system, of the total exergy of input resources of about 52,266 MJ, about 48,725 MJ came out as useful products including biodiesel, recovered methanol, and water. The overall exergy destruction recorded was about 3,539 MJ for 1 ton of palm biodiesel produced. The exergy efficiency of the biodiesel production system was about 93.2 %. Figure 7.5 shows the exergy destruction contributions by the unit operations within the biodiesel production system.

All the production subunits recorded high exergy efficiencies above 97 % with the washer having the highest at about 99.6 %. The CPO purification unit recorded

Table 7.2 Standard chemical exergy values of materials used in oil palm cultivation, palm oil milling, and biodiesel production

Substance	Standard chemical exergy ($Ex_{ch, i}^0$) (MJ/kg)
Biodiesel	35.55
Crude palm oil (CPO)	36.26
Diesel fuel	42.70
Electricity	1.00
Empty fruit bunches (EFB)	18.50
Fresh fruit bunches (FFB)	40.21
Glycerol	22.30
Methanol	22.44
NPK Fertilizer	18.57
Oil palm fronds (OPF)	19.93
Oil palm seeds	17.71
Oil palm seedlings	18.09
Oil palm trunks (OPT)	20.11
Palm kernel nuts (PKN)	31.45
Palm pressed fiber (PPF)	17.77
Pesticides	19.13
Phosphoric acid (H_3PO_4)	0.914
Polythene bags	18.57
Sodium hydroxide (NaOH)	1.873
Solar energy	0.04595
Steam	0.526
Water	0.049

Source Rivero and Garfias (2006), Szargut et al. (1988), Ofori-Boateng et al. (2012c), Ojeda et al. (2011)

the lowest exergy efficiency of about 97.4 % and contributed about 34 % of the total exergy destruction for the whole plant. The total useful energy destroyed in the biodiesel production unit was about 3,447 MJ (exergy efficiency of 93.2 %) which is closer to the reports from other researches, which utilized different feedstocks. Jaimes et al. (2010) has also reported that about 42 % of the total exergy destruction for the biodiesel production system was contributed by the purification and separation systems. Ofori-Boateng et al. (2012a, b, c) reported a total exergy destruction of about 1,262 MJ (exergy efficiency of 83 %) and 1,275 MJ (exergy efficiency of 92 %) for the conversion of microalgal and *Jatropha curcas* oil into biodiesel, respectively, considering 1 ton of biodiesel produced. The conversion of microalgal oil into biodiesel has again been assessed by Peralta et al. (2010) and Sorguven and Ozilgen (2010) to have exergy destructions of about 7,232 MJ (79 % exergy efficiency) and 190 MJ (70 % exergy efficiency), respectively, for 1 ton biodiesel produced. Talens et al. (2010) calculated the exergy efficiency of a production system for 1 ton biodiesel from used cooking oil to be as high as 98 % with the assumption that all waste streams are utilized. Comparing these reports with the results of this study, palm biodiesel is considered more exergetically efficient than microalgal and jatropha biodiesel

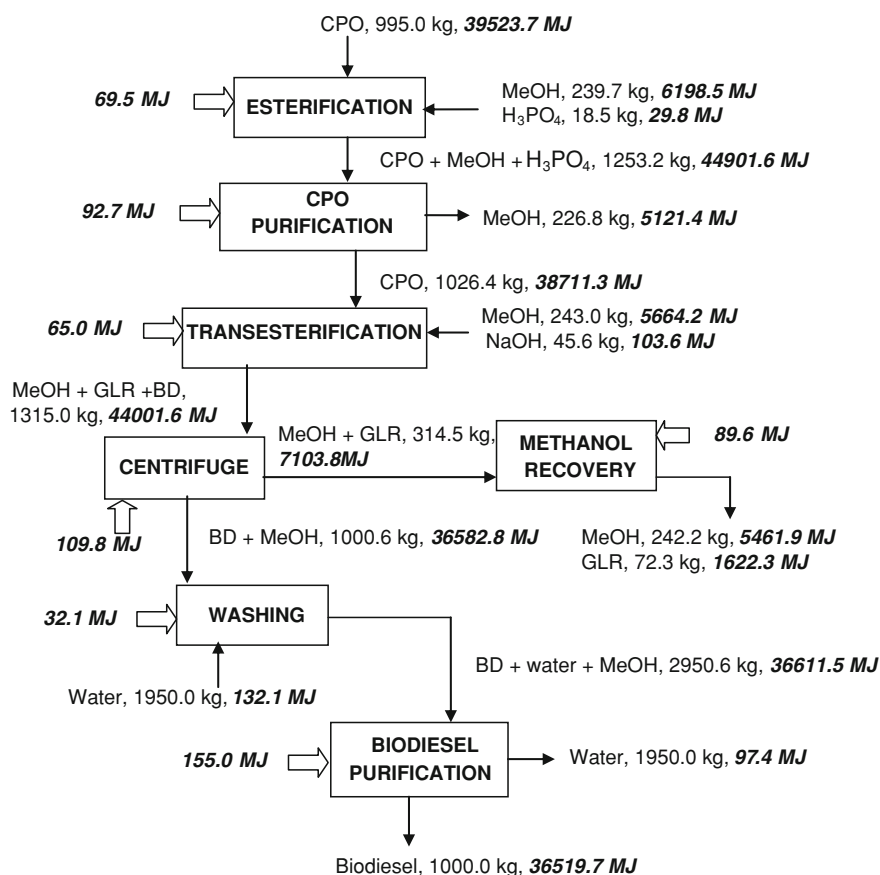


Fig. 7.4 Exergy balance for biodiesel production from CPO

production systems when all waste streams like wastewater, glycerol, etc., are utilized for value-added bioproducts.

Energy integration as well as efficient equipment design could reduce these destructions in order to make the system more thermodynamically sustainable. Again, separation parameters like retention time must be carefully chosen and monitored in order to ensure efficient operations by the separation equipment.

This study assumed the treatment and possible utilization of all wastes generated from each of the unit operations. Methanol was recovered for reuse while wastewater from the separation units was considered to be treated before discharge. With all these assumptions not made, the system would have recorded much higher exergy destruction which would eventually reduce the exergy efficiency.

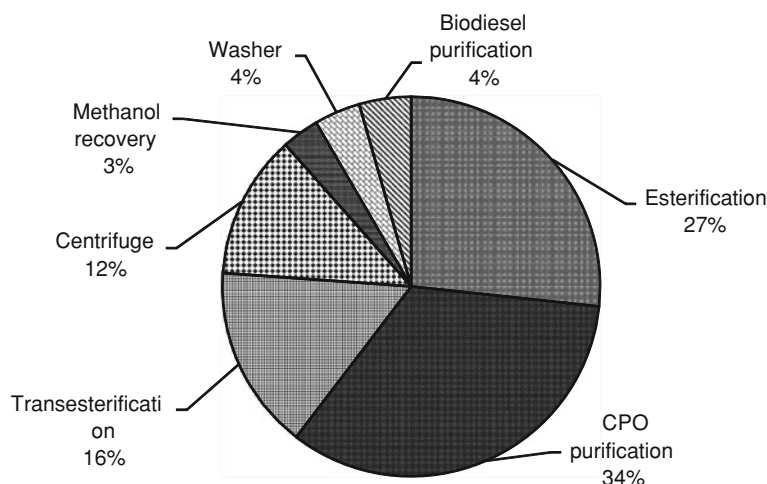


Fig. 7.5 Exergy destruction contributions by unit operations in the biodiesel production system

7.4.4 Exergy Analysis of Bioethanol Production from Oil Palm Fronds (OPF)

The data used in this study were obtained from published research reports (Goh et al. 2012; Ojeda and Kafarov 2009; Hamelinck et al. 2005; Ofori-Boateng and Lee 2013).

Separate hydrolysis and fermentation of OPF is chosen as case study for this section and this method involves three major processes namely pretreatment, hydrolysis (or saccharification), and fermentation. Bioethanol production from lignocellulosic materials like OPF requires the removal of lignin and other extractives in order to expose the holocellulose and increase cellulose crystallinity for easy enzyme or acid catalyst activities. The pretreatment stage is vital to facilitate the production of sugars from the cellulosic material as it has been found that bioethanol production from nonpretreated biomass generated less than 20 % sugar yield as against over 90 % yield for pretreated biomass (Hamelinck et al. 2005).

During the pretreatment process, the OPF obtained from the oil palm plantation were washed, cut into smaller pieces, dried, and milled in order to increase its surface area for maximum chemical/enzyme penetration. The pretreatment stage is found to be one of the energy intensive stages for the production of sugars from lignocellulosic materials (Ojeda and Kafarov 2009). Again, the pretreatment stage for cellulosic ethanol generates large quantities of utilizable wastes that are not tapped for value-added bioproducts. Thus there must be the need to assess its exergetic efficiency in order to improve the process for sustainable bioethanol production. Some cost effective ways of pretreating lignocellulosic materials for

bioethanol production include the applications of steam explosion or hot water, dilute acid/alkaline, lime, ammonia, etc. (Moiser et al. 2005). In this study, steam explosion is chosen as a pretreatment method. The pretreated OPF then undergo acid hydrolysis and fermentation separately.

Hydrolysis is a chemical reaction which converts complex polysaccharides (e.g., starch, cellulose, chitin, glycogen, etc.) in biomass into simple sugars (i.e., monosaccharides) such as glucose (dextrose), galactose, fructose, hexose, xylose, ribose, etc., which is commonly catalyzed by enzymes, acids, and alkaline. Saccharification of the prehydrolysate with dilute sulfuric acid (H_2SO_4) for the conversion of the cellulose into sugars is used in this study. H_2SO_4 is preferred as catalyst for acid hydrolysis because it remains in the hydrolysate (after neutralization with NaOH) as nutrients for microorganisms during fermentation and eventually improves the economics of the process (Gómez et al. 2006). The separation process is therefore eliminated hence, reduction in 'energy' use. Glucose yield of about 70–85 % (compared to about 95–99 % for enzymatic hydrolysis) is achieved with acid hydrolysis due to the production of furfural (Gómez et al. 2006). In this study, about 5 wt% acid concentration is used for the hydrolysis of steam exploded OPF. The hydrolysate then enters the fermentation reactor where the sugars are converted into bioethanol.

Fermentation is a biochemical reaction which converts the simple sugars from the hydrolysis reaction into bioethanol (with carbon dioxide as by-product) with the help of yeast (mostly *Saccharomyces cerevisiae*). In this work, fermentation of the sugars was aided by baker's yeast (*S. cerevisiae*). The resulting bioethanol which contains water and impurities is separated by stripping and dehydration using molecular sieves.

The fresh OPF chemical compositions include 20.5 % lignin, 49.8 % cellulose, 33.7 % hemicellulose, 2.4 % ash, and 4.5 % extractives (Wan Zahari et al. 2004). After pretreatment, the considered compositions of the OPF prehydrolysate for simulation are 16.53 % lignin, 38.52 % cellulose, and 30.95 % hemicellulose (Goh et al. 2012).

A functional unit of 1 ton bioethanol is chosen for the exergy analysis in this study. In order to produce 1 ton of bioethanol, 3 tons of OPF is used as the feed mass. All wastes within the bioethanol production system are considered untreated. The production of input resources as well as the utilization of lignin (as by-product) is not part of the system boundary. Steady-state reaction conditions as well as the NRTL model for the calculation of the activity coefficients for the components due to the presence of liquid–vapor phases (Prausnitz et al. 1980). Hexose sugars were represented by glucose while pentose sugars were also represented by xylose. Table 7.3 summarizes the production conditions used for the mathematical modeling with Aspen Plus software.

Chemical exergy is calculated using the total mass and chemical composition of the substance of interest together with the specific or standard chemical exergy which is obtained from Szargut et al. (1988). For instance, the specific chemical exergy of OPF is found from the correlation by Eq. 7.16 (Szargut et al. 1988):

Table 7.3 Production conditions for bioethanol production from OPF

Production stage	Production conditions	Sugar yield (%)	
		Glucose	Xylose
Pretreatment	Steam explosion, 160 °C, 1 atm		
Saccharification (hydrolysis)	Dilute H ₃ PO ₄ , 2.5 % w/v, 175 °C, 3.5 atm	35.8	67.8
Fermentation	Yeast (<i>Saccharomyces cerevisiae</i>), 20 FPU/g, 303 K, 1 atm		

Sources Millati et al. (2002), Palmqvist and Hahn-Hagerdal (2000), Goh et al. (2012)

$$\begin{aligned}
 Ex_{ch,i}^0(OPF) = & \left[0.498 \times Ex_{ch,i}^0(\text{cellulose}) \right] + \left[0.337 \times Ex_{ch,i}^0(\text{hemicellulose}) \right] \\
 & + \left[0.205 \times Ex_{ch,i}^0(\text{lignin}) \right] + \left[0.024 \times Ex_{ch,i}^0(\text{Ash}) \right] \\
 & + \left[0.045 \times Ex_{ch,i}^0(\text{Extractives}) \right]
 \end{aligned}
 \tag{7.16}$$

The standard chemical exergy values for the major compounds used in this study are shown in Table 7.2 with references from Szargut et al. (1988). For other compounds whose standard chemical exergy values are not found in the literature, a similar correlation in Eq. 7.16 is used to compute them. For chemical exergies of utilities involved with electricity, 1 MJ of electrical energy was assumed to correspond to an exergy flow of 1 MJ (Talens et al. 2007).

Physical exergy of each stream was found with the help of Aspen Plus software version 2006 after simulation and other values from Wooley and Putsche (1996). The enthalpy and entropy values generated from the software were used with the help of Eq. 7.3 to calculate for the physical exergies. Total exergies were then found for each stream and the calculations for exergy destructions (both internal and external) for every unit operation within the production system were calculated accordingly. Table 7.4 shows the standard chemical exergy contents of input and output resources for the production of bioethanol from OPF. Figure 7.6 summarizes the exergy balance estimation for the OPF bioethanol production.

Considering the whole bioethanol production system, about 36,815 MJ of ‘quality energy’ was destroyed for every ton of bioethanol produced from OPF. The exergy efficiency of the system was 52.5 % when it was assumed that the lignin could be used in the combined heat and power generation plant in the palm oil mills while wastewater could be treated and recycled for use in the bioethanol production system. Of about 69,812 MJ of useful energy in OPF that underwent the processing, about 37.1 % was destroyed in order to obtain the final product, bioethanol. The exergy efficiency would be lower if lignin and waste streams are not utilized for value-added bioproducts.

The feed preparation subsystem consisted of washing, milling, and drying units. For a production of 1 ton bioethanol from OPF, this subsystem contributed about 23.5 % of the total exergy destroyed. However, the feed preparation unit had an

Table 7.4 Standard chemical exergy values of materials used in palm bioethanol production from OPF

Substance	Standard chemical exergy ($Ex_{ch,i}^0$) (MJ/kg)
Acetic acid	4.94
Ash	0.202
Bioethanol	24.55
Carbon dioxide (CO ₂)	0.443
Cellulose	12.52
Diesel fuel	42.70
Electricity	1.00
Extractives (mainly phenolic compounds)	14.23
Furfural	11.31
Glucose	12.72
Hemicellulose	9.12
Lactic acid	8.44
Lignin	18.79
Oil palm fronds (OPF)	19.93
Sodium hydroxide (NaOH)	1.873
Sulfuric acid (H ₂ SO ₄)	1.66
Steam	0.526
Water	0.049
Xylose	10.02
Yeast	7.93

Source Rivero and Garfias (2006), Ofori-Boateng et al. (2012a), Ojeda et al. (2011)

exergy efficiency of 88.5 %. The total exergy of wastes from this unit was 779.9 MJ which resulted from the discharge of wastewater used in the washing of OPF before drying and milling. If the wastewater is not treated and recycled, the overall exergy efficiency would reduce. Fossil fuel use in drying and other unit processing contribute to emissions into the environment hence reduction in the efficiency of the system thus fossil fuel use must be minimized.

Steam explosion subsystem which consisted of steam explosion tank and drying unit contributed the highest exergy destruction of about 59.3 % for the whole bioethanol production. About 69.9 % exergy efficiency was recorded for the steam explosion of OPF for 1 ton bioethanol production. Most of the valuable energy available within the input resources (mainly OPF with total exergy of 61,778 MJ) to perform work was degraded (to an exergy content of 41,333 MJ) due to entropy generation within the system leading to irreversibilities. The efficient design of the steam explosion reactor as well as suitable operation conditions would help reduce some of these inefficiencies in exergy contents of materials that come out as products from the reactor.

The hydrolysis reactor also recorded the next highest exergy destruction after steam explosion unit. The overall exergy efficiency for the hydrolysis reactor was about 72.8 %. The chemical and thermal processes that occurred in the hydrolysis reactor contributed to entropy generation, hence exergy destruction. Minimization

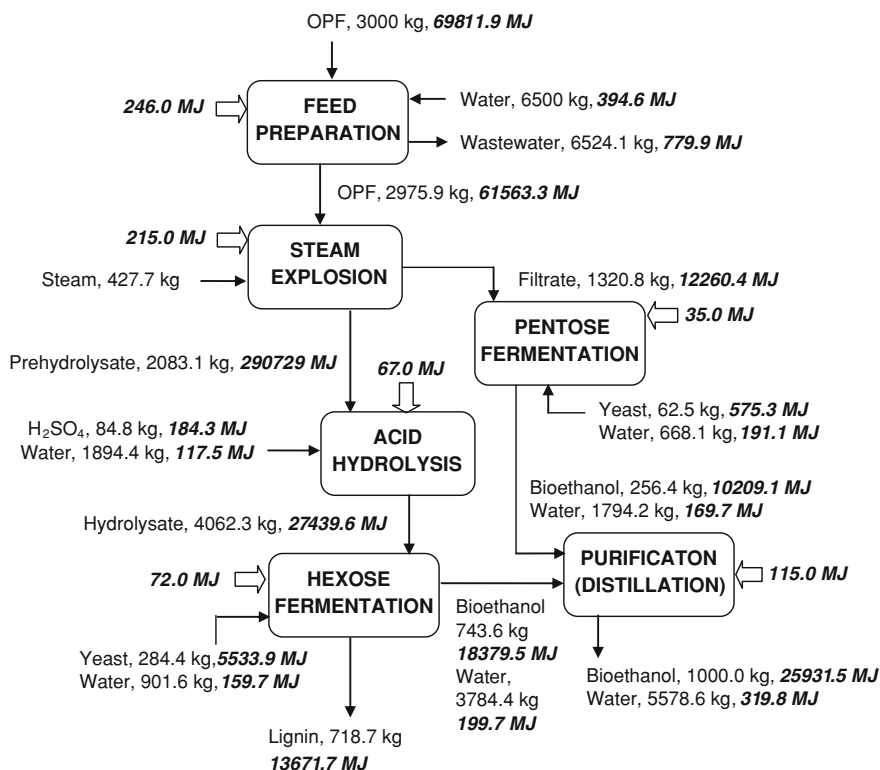


Fig. 7.6 Exergy balance for bioethanol production from OPF

of chemical use or their replacement with enzymes could help reduce the exergy destruction though enzymes are costly.

The fermenters (xylose and glucose fermentation reactors) also recorded some amount of irreversibilities due to the inhibition effect of glucose and xylose accumulations within the reactors (Ojeda and Kafarov 2009). The enzyme velocity is therefore reduced at low substrate concentration, hence causing the reduction in exergy efficiencies. The exergy efficiency of the pentose fermenter (88.5 %) was lower than that of the hexose fermenter (97.1 %) due to process inefficiencies leading to high exergy destruction in the pentose fermenter. The pentose and hexose fermenters contributed about 7.8 and 2.8 % to the total exergy destroyed in the bioethanol production system.

On the other hand, the purification unit recorded about 282.7 MJ of exergy destruction, which is about 0.82 % of the total exergy destroyed by the bioethanol production system. The overall exergy efficiency of the bioethanol purification unit was about 90.3 %. In this unit, entropy generation was minimal perhaps due to efficient process and equipment design. The process conditions were favorable which contributed to minimal destruction of exergy of the bioethanol.

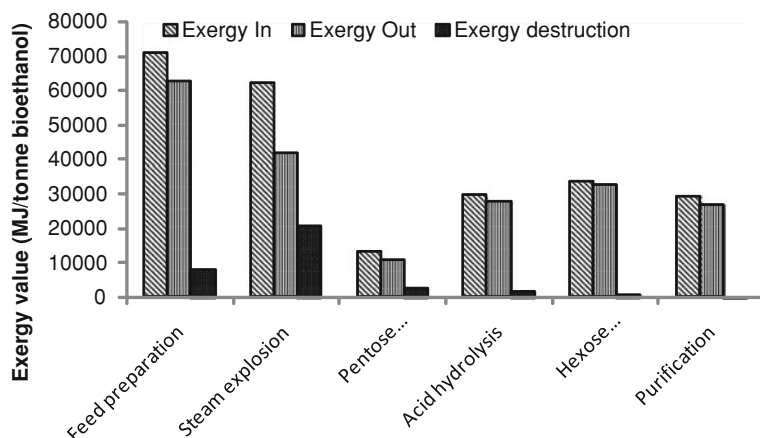


Fig. 7.7 Exergy destruction contributions by unit operations in bioethanol production system

The exergy content of OPF was, however, degraded from 69,812 to 25,932 MJ with about 37.1 % useful exergy destroyed in the OPF. The bioethanol could gain high exergy content when the whole production process is improved through process and equipment design as well as utilization of wastes for value-added bioproducts (Ofori-Boateng and Lee 2013). Figure 7.7 shows the contributions of exergy destruction by the unit operations within the bioethanol production system for 1 ton bioethanol production from OPF.

7.4.5 Exergy Analysis of an Integrated System for Biomethane and Bioelectricity Production from POME

The system boundary for the integrated biogas and bioelectricity production from POME used for the exergy analysis in this section did not include the production of all raw materials, equipment, and buildings. The digestate generated after anaerobic digestion was considered as a useful material that can be used in the oil palm plantation as biofertilizer.

In a typical palm oil mill where POME is treated in open ponds, the POME generated from processing 1 ton of FFB/h is able to produce about 333 m³ biogas which comprises about 64 % methane, 35 % CO₂, and traces of hydrogen sulfide and water vapor (Ma 1999). This amount of POME can produce about 115 MJ electricity to add to the bioenergy used in the mill.

Joanta (1996) estimated a total of about 1.04 MW bioenergy that could be generated from about 12,000 m³ of biogas produced per day from POME obtained from the processing of about 60 tons of FFB/h. In Malaysia, there exist over 400 palm oil mills with a total installed CHP capacity of about 261.1 MW, which are capable of generating over 1.88 MW/h of bioelectricity (NKEA, 2011).

In this study, it is assumed that POME generated from the palm oil mill is directly charged into the homogenizer where mixing is done to enhance microbes activities for high biogas yield. POME contains about 95 % water, 4 % residual oil (FFA content of 30–70 %), and 1 % sediments. About 1 m³ of POME, which is equivalent to 1,500 kg, can generate about 28 m³ of biogas and a m³ of the biogas produced can generate about 0.3453 MJ bioelectricity. About 97 % of the POME after anaerobic digestion remains as the digestate which can be used as biofertilizer (Sežun et al. 2010).

The homogenized POME then enters the anaerobic digester for fermentation to occur. About 80–90 % of palm oil mills in Malaysia use the anaerobic and facultative ponding systems for treating POME because they are relatively cheap (Ma and Ong 1985). However, there are some commercial palm oil mills that treat their POME using closed-tank anaerobic bioreactors for biogas capture (Quah 1987) though they require long residence time. Exergy analysis is carried out on a close-tanks anaerobic digester which operates at mesophilic temperature (37 °C) (Yejian et al. 2011). For a kilogram of POME processed, about 0.23 MJ of energy (both electrical and heat) is needed by the anaerobic digester to produce the biogas (Berglund and Börjesson 2006; Börjesson and Berglund (2007)).

The biogas produced from the anaerobic digester is a mixture of CH₄, CO₂, H₂S, and traces of water vapor. In order to upgrade the biomethane as the main product for bioelectricity production, a scrubbing unit is employed and the CO₂, H₂S, and water vapor are trapped by a gas stack while the biomethane goes into the CHP plant for electricity generation. What most palm oil mills do is to capture their biogas, and flare or release them into the atmosphere causing environmental burdens (Lantz et al. 2007). The biogas purification unit also requires about 0.0018 MJ of energy to process 1 kg of biogas (Murphy and McCarthy 2005) before being fed into the gas turbine for bioelectricity generation. Energy use within the biogas plant is assumed to be sourced from fossil fuel. Water consumption for the removal of impurities from the biogas is assumed to be 1 kg for every cubic meter of biomethane generated (Benjaminsson et al. 2010).

Biomethane then enters the CHP plant for bioelectricity generation. The CHP plant consists of compressors and gas turbines, which have pistons within which the biomethane is combusted. The energy resulting from the biomethane combustion is used to rotate a shaft which converts chemical energy in the biomethane into mechanical energy. This energy then powers an alternating current shaft, which eventually produces the electricity through magnetism. A functional unit of 1 MJ bioelectricity is chosen for this study.

Table 7.5 shows the standard chemical exergies of the main input and output resources for bioethanol production from OPF. Data used for the materials and energy balance calculations were obtained from published research reports (Yejian et al. 2011; O-Thong et al. 2012; Hosseini and Abdul Wahid 2013). Figure 7.8 summarizes the exergy balance calculations for the production of biomethane and bioelectricity from POME.

The main inputs into the biomethane and bioelectricity generation systems were POME, heat, and steam. The total exergy of these input resources was about

Table 7.5 Standard chemical exergy values of the major input and output resources of bio-electricity generation from POME

Substance	Chemical formula/ composition	Density (kg/ m ³)	Standard chemical exergy ($Ex_{ch,i}^0$) (MJ/kg)
Methane	CH ₄	0.66	51.81
Carbon dioxide	CO ₂	1.98	0.443
Hydrogen sulfide	H ₂ S	1.36	23.83
POME	H ₂ O + CPO + sediments	400.00	0.166
Water	H ₂ O	1.00	0.049
Bioelectricity	–	–	1.00
Biogas	CH ₄ + H ₂ S + H ₂ O + CO ₂	–	97.12

Source Rivero and Garfias (2006), Szargut et al. (1988), Szargut (2005), Ayres and Ayres (1998)

123.5 MJ per MJ of bioelectricity produced. With about 116.3 MJ of exergy resulting as outputs (excluding CO₂ and H₂S), the overall exergy efficiency for the integrated system for biogas and bioelectricity production from POME was about 94.2 % for 1 MJ bioelectricity generated. The whole production system recorded a very low exergy destruction of 7.2 MJ resulting from entropy generation due to materials and energy dispersion during the process. The exergy efficiency could increase if possible utilization of CO₂ is considered while the capacity for electricity generation also increases. Begum and Saad (2013) have reported that the generation of electricity from POME is economically and technically sustainable based on their techno-economic assessment. Their conclusion is tantamount to the findings of this study that bioelectricity from POME is thermodynamically sustainable but still needs further improvement.

Though energy use by the anaerobic digester was highest, it recorded a negative exergy destruction (–1,040 MJ) as a result of high quality exergy of biogas (991 MJ) produced from the POME with low exergy value (33 MJ). The total input exergy was about 66 MJ compared to 1,106 MJ of useful exergy in the products. The POME (which is wastes) was, therefore, upgraded to a high quality energy value product (biogas) by about 1,040 MJ for about 155 kg of POME processed. Martin and Parsapour (2012) have also reported a similar scenario for which the exergy content of biogas produced from brewer's BSG was upgraded by 6,136 MJ for 60,000 tons of BSG processed. Comparing these results, it could be seen that biogas production from POME is of high quality in terms of exergy compared to that obtained from BSG.

However, when the biogas was purified to remove the water vapor, CO₂, and H₂S, the exergy content of the output (biomethane) was reduced to about 198 MJ. The purification unit recorded the highest exergy destruction of about 811 MJ followed by the CHP system (222 MJ). Entropy generation due to the dissipative effects of CO₂ and H₂S by the purification system could be a cause for increased exergy destruction. In appropriate process conditions and inefficient equipment design were among the factors which caused the increase in exergy destruction within the purification and CHP systems.

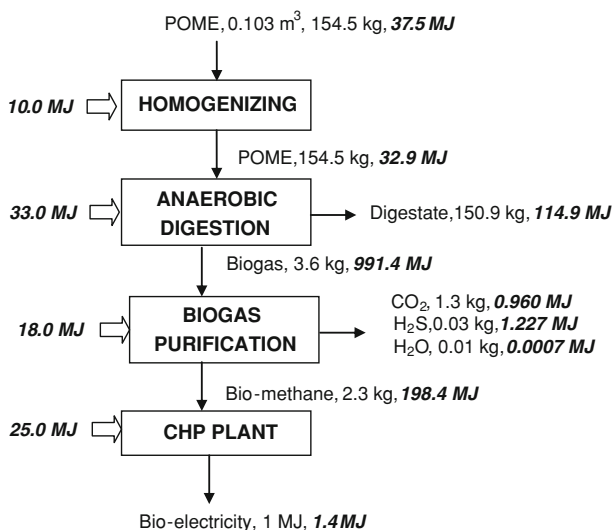


Fig. 7.8 Exergy balance for biogas and bio-electricity production from POME

7.4.6 Exergy Analysis of the Production of Palm Kernel Shells (PKS)-Derived Briquettes

Biomass briquetting is the process of densifying raw biomass into compact solid composites of various shapes and sizes using pressure and heat. Briquettes are high-energy value solid biofuels that burn with little smoke compared to biomass that are directly combusted. In order to reduce the emissions from palm oil mills' CHP plants, solid palm biomass like PKS, EFB, OPF, OPT, etc., can be converted into briquettes that can be used as boiler fuels for steam and electricity generation. In the palm oil mill where steam and bioelectricity are produced from the solid palm biomass generated as wastes, PPF is the most abundantly utilized boiler fuels. Only a small percentage of PKS generated are used as boiler fuels with insignificant or no EFB utilized. EFB contains high moisture content, which need additional pretreatment before firing in the boiler. However, most CHP plants in palm oil mills do not have these facilities and hence make use of only PPF and PKS, though EFB is a potential feedstock for bioelectricity generation.

Briquettes made from PKS are found to possess high calorific value (18–20 MJ/kg) compared to most briquettes from other sources. PKS briquettes burn with less smoke and CO₂ emissions, contain less dust and impurities, have low moisture content, and can be easily transported (risk of sparks that lead to fires are avoided) unlike gaseous and liquid biofuels. Briquettes are sulfur-free solid biofuels that burn with no generation of fly ash. PKS briquettes are low cost palm solid biofuels that can be utilized in boilers for efficient heat and power generation compared to

PPF, EFB, etc., that are fired directly in boilers for steam and bioelectricity generation.

PKS briquettes making begin with the pretreatment stage which comprises screening, drying (either by sun or flash dryer), and milling into very small sizes (in some cases, the PKS are milled to powders). Alternatively, torrefaction, pyrolysis, or carbonization can be used as a way of removing moisture from the biomass before briquetting. The method used to dry the biomass before pressing depends on the applications for which the product would be used. For instance, a piston press can be used to make briquettes that can be used for a variety of applications. The PKS after pretreatment is transported by pneumatic system to containers that are fixed to the briquetting press. Cyclones are attached for dust and solid particles collection during briquetting. Natural binder from the biomass (like lignin) binds the surfaces of the biomass together upon rise in temperature during briquetting. The briquetting process transforms the original biomass into biofuels with unique characteristics that are capable of burning efficiently. For example, screw extrusion can produce toroidal or oval-shaped homogeneous briquettes with large surface area that could burn faster and efficiently just like coal in a cogeneration plant. The production of briquettes can release significant amounts of emissions in the form of dust and particles during raw material handling, pretreatment, and pressing. The wastes generated in a briquetting plant are mainly the solid residues from the biomass used as raw material.

The main unit operations considered in this study are drying, grinding, briquette pressing, and cooling. The PKS with moisture content of about 30 % is first dried to moisture of about 10 % using a conventional oven dryer or flash dryer. Open sun drying is a cheaper alternative for drying the PKS but it is found to alter the quality of the raw material due to poor ventilation, contaminations by impurities, etc. The dried PKS are screened to remove unwanted materials before grinding. Examples of unwanted materials that may be present in the PKS before processing are stones, fibers, palm kernels, etc. In this study, the manual briquetting technology that employs the screw press type briquetting machine (commonly called the extrusion machine), was used to obtain the PKS briquettes without any binding material. The PKS briquettes were cooled in the open air to reduce its temperature before packaging. A ton of PKS briquettes is chosen as the functional unit. For the production of 1 ton PKS briquettes, about 1,002 kg of PKS is needed. The standard chemical exergies of PKS and PKS briquettes are 25.8 and 20.1 MJ/kg, respectively (obtained from Eq. 7.16). Figure 7.9 shows the exergy balance estimation for the production of briquettes from PKS.

From Fig. 7.9, the main input into the briquetting unit is the PKS with about 27,912 MJ exergy content. The product of interest is PKS briquettes, which according to Fig. 7.9, contained about 21,184 MJ exergy. This implies that PKS were degraded by 24 % in terms of exergy when they were processed into briquettes. For the production of 1 ton PKS briquettes, about 7,039 MJ of exergy was destroyed making the production process 75 % exergetically efficient. The total exergy of wastes was about 62 MJ which was contributed mainly by the impurities

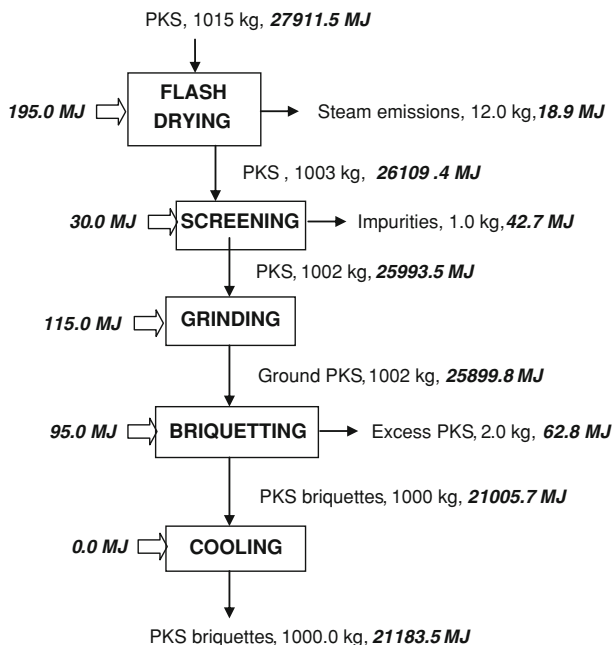


Fig. 7.9 Exergy balance for PKS Briquetting Processes

which were part of the PKS before processing and were removed after the screening process.

However, the individual unit operations recorded exergy efficiencies higher than 80 %. On the other hand, the exergy destructions were higher for some of the units. For instance, the briquetting and drying units recorded high exergy destructions of about 4,926 and 1,978 MJ, respectively. These units used high amount of energy for processing. With about 25,995 MJ of exergy of resources that entered the briquetting unit, about 19 % was degraded during processing because of entropy generation. The briquetting press uses high amounts of energy and pressure for extrusion causing resource or matter dissipation, hence exergy destruction. Appropriate choice of process conditions and equipment design efficiency would help reduce the exergy destruction.

The cooling process was the most exergetically efficient with resource input upgrade of about 178 MJ exergy. Because an open air or natural ventilation was used to cool the briquettes, energy input was zero.

The screening and grinding processes recorded low exergy destruction of about 103 and 209 MJ, respectively, compared to the other units. Figure 7.10 shows the summary of exergy destruction distributions by the unit operations for PKS briquetting.

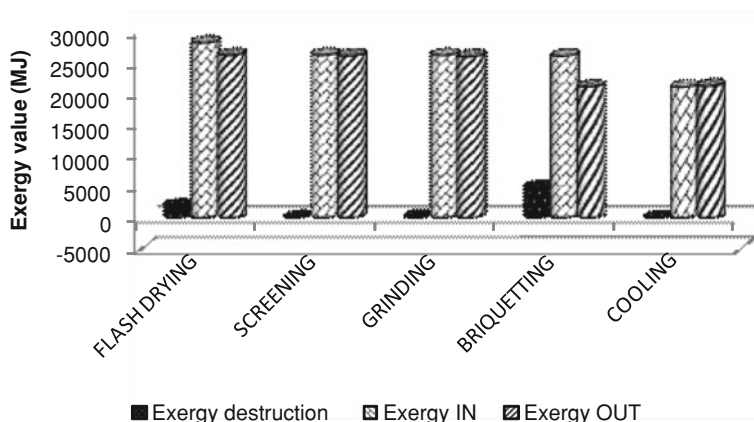


Fig. 7.10 Exergy Destructions occurring in PKS briquetting production system

7.5 General Improvement Options for Palm Biofuels Production Systems

Several authors have suggested various ways of improving the thermodynamic sustainability of biofuels production processes (Linnhoff 1983; Leites et al. 2003; Sama et al. 1989; De Swaan and Van der Kooi 1993).

Agricultural systems such as oil palm cultivation units can be improved thermodynamically by the reduction of chemical fertilizers, fossil fuels, and other input materials that have high exergy contents. The use of organic fertilizers, solar powered irrigation systems, and other best management practices (see Chap. 4, Table 4.1) for sustainable oil palm biomass production must be encouraged.

Palm oil milling processes are also found to degrade significant amounts of input exergy resulting in low efficiency of the system. The utilization of wastes like EFB, PPF, and PKS for value-added bioproducts must be the goal of all palm oil millers as this would decrease the exergy of wastes into the environment. Technically, inefficient design of equipment and processes without conformity to the sustainability standards set by the RED-RSPO, can lead to high exergy destruction, thus the need to avoid these occurrences.

For biodiesel production from palm feedstocks like CPO, PFAD, CPKO, etc., can be improved drastically by replacing the conventional distillation columns with supercritical methanol method which make use of the reactive petlyuk column (Gomez-Castro et al. 2010). This configuration is found to reduce the energy consumption by 45 % compared to conventional distillation trains because it does not present the re-mixing effect (Triantafyllou and Smith 1992), hence highly recommended for biodiesel production. This technique can be applied to bioethanol and biomethanol production units for palm biofuels production. Thermally coupled reactive distillation process for biodiesel production has been shown to be sustainable because the column uses vapor–liquid interconnections to achieve heat

transfer by direct contact with the streams, hence no need for double condensers and reboilers (Gomez-Castro et al. 2008).

In a palm biofuel production system where the processes involve heat transfer (e.g., using heat exchangers, dryers, evaporators, distillation columns etc.), entropy generation becomes an important parameter to study and optimize. For streams which have the same heat capacities, the driving force (e.g., temperature, pressure, etc.) is also the same and in such situations, the driving force can be minimized (in order to minimize entropy generation leading to exergy destruction) by increasing the heat transfer area, or the overall heat transfer coefficient. This can further lead to a reduction in heat duty, especially with distillation columns, where the number of feed stages and reflux ratios are optimized. For complex systems where the driving force may keep changing, the design of the equipment plays an important role. For instance in a distillation column, the column height can be increased or the feed stage can be increased in order to approach equilibrium at one or two points.

The exergetic efficiencies of palm biofuels production systems can be improved by process adjustments such as optimization of the FFA ratio in the oils (for biodiesel production) to increase the purity and yield of the product. This can be applied to biogasoline and bioethanol production systems where the feed oils or holocellulose must be of high purity before conversion. Again, the exergy destruction due to heat loss can be minimized by reusing in-process heat, thereby minimizing the energy supply.

Also, all methanol recovery units as well as separation equipment must be optimized, i.e., reducing the reflux ratio to reduce heat duty. There is maximum exergy loss in the separation units of the plant when the temperature change is not constant (nonisothermal). This can be replaced by isothermal process equipment, e.g., with the extractive decanter. To have a realistic size of equipment and make a given process take place in finite time, there is a greater need for a minimum driving force (Leites et al. 2003). It is thus, always necessary to give allowances for the minimum potential difference while carrying out the analysis of a system with the aim of reducing the exergy loss. For the design and development of energy and exergy efficient production systems, turbulence and vorticity on entropy production in different processes as well as the influence of heat on the system and chemical composition of the inputs are vital for consideration. Also, work extraction devices such as the centrifuge should be properly designed to extract the maximum exergy contained in the product.

Input resources like catalysts, etc., have serious effects on the efficiency of the biofuels production systems. Performing the mass and heat balances makes it possible to determine whether a particular heat source and/or sink present an appropriate option for the given duty. In the distillation columns, it was observed that the irreversibility increased with recirculation or increased reflux ratio and decreased number of ideal stages.

To increase the exergy efficiency and use energy in a more rational way, renewable energy resources like solar energy, which have low emissions into the environment, may reduce the external exergy destruction. For instance, in situations where open sun drying can be used without problems, it should be an

alternative to flash drying or any other means of drying using energy from non-renewable sources. Fossil fuels and electricity from fossil fuel have high exergies and must be used in low amounts. Electricity can be exploited with low exergy losses with high coefficient of performance heat equipment and pumps. Use of fossil fuels for thermal purposes must be avoided and replaced with solar energy or other possible renewable and clean means of heating. Though the exergy content of the sun's energy is high, its exploitation with even low exergy efficiencies may produce a better impact (because it is a renewable energy source) compared to fossil fuel. Fossil fuel releases more emissions into the environment upon combustion hence contributing to exergy inefficiencies but solar energy use shifts the production to more renewability or sustainability.

The thermodynamic improvement potential is, however, not directly proportional to the cost of unit operation thus the reduction of irreversibilities may not necessarily lead to lower cost of equipment. Therefore, the cost factor may render the requirement for thermodynamic perfection unattractive and ambiguous. For instance in a dryer or heat exchanger, where the irreversibility is mainly due to heat transfer, energy loss can be achieved either by increasing or reducing the temperature coefficient which may either increase or decrease the cost of production. Again, the temperature difference between the air supply and the supply temperature of the product affects the exergy consumption in the drying process. According to Keey (1978), if air recycle can be done effectively in continuous drying, the gain in thermal economy becomes worthwhile and performance of these systems can be improved effectively. This study, however, did not consider the cost aspects of the production plants since the input and output exergies can justify the thermodynamic sustainability of the plant.

7.6 Conclusion

The thermodynamic feasibility of palm biofuels production systems were assessed based on the literature values which were simulated in Aspen Plus software. Potential causes and improvement options have been discussed in this chapter for sustainable palm biofuels production. The production of palm biodiesel, bioethanol and bioelectricity from oil palm wastes would be exergetically efficient when process improvement options are critically taken into consideration.

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Chapter 8

Social and Policy Issues Affecting the Sustainability of Palm Biofuel Production

Abstract Social sustainability of the palm biofuel industry stresses on the need to produce favorable social and distributional effects like employment, food security, conservation of cultures, equality in sharing between involving parties, technological advancement and training, etc., that would continue to benefit the future generation. The expansion of the oil palm biofuel industry in reaction to the climate change mitigation has necessitated the industry over social, environmental, and political sustainability of palm feedstocks production. Though the production of oil palm biomass and subsequent conversion into biofuels have positive social impacts, some research reports reveal the high rate of unemployment, homelessness and poverty among rural folks who are engaged in oil palm cultivation. This chapter outlines the factors that affect the socio-political sustainability of palm biofuels where real situations on the ground are discussed and suggestions made.

Keywords Socio-political sustainability • Biofuels sustainability • Palm biofuels • Oil palm biomass • Oil palm wastes • Oil palm cultivation • Sustainable palm biofuels

8.1 Introduction

Asia is currently the leading producer of palm biofuels especially biodiesel with Malaysia being the regional leader. In 2010, Malaysia and Indonesia contributed about 540 and 400 million liters of palm biodiesel to the world's total palm biodiesel production capacity (Slette and Wiyono 2011; Teoh 2010). These two countries are forecast to double their production capacities by 2019 hence expansion in their oil palm industries (Hoh 2009). These expansion projections have become subject of debate as presently some view the oil palm as a clean economic source of energy and food as well as a major contributor to climate change mitigation and rural livelihoods (Basiron 2007). On the contrary, some authors (Fitzherbert et al. 2008; Sheil et al. 2009; Marti 2008; Colchester 2010; Bringezu et al. 2009) have branded the oil palm as a contributor to potential social, environmental, and economic implications. As a

result of these outcomes, the Malaysian and Indonesian governments are leaving no stone unturned to protect and improve the sustainability of palm biofuels production particular the oil palm production stage which is found to contribute to negative social and environmental impacts (Dillon et al. 2008). In view of this, the governments of palm oil producing countries especially Malaysia and Indonesia have made policies and regulations concerning palm biofuels production and consumption with incentives and subsidies for the producing companies. The Roundtable on Sustainable Palm Oil (RSPO) and the Indonesia Sustainable Palm oil programs have come to help ensure the responsible production of palm oil throughout the region for social, environmental, thermodynamic, and political sustainability for the oil palm industries.

Socio-political sustainability is the least advanced or discussed to the highest degree when it comes to biofuels sustainability. However, as reported by Colchester (2010), Sheil et al. (2009) and other researches, the production of palm biofuels can result in worse cases of social impacts which can outweigh the benefits that biofuels bring. Oil palm cultivation for instance has been assessed in this book (see Chap. 5) have many environmental benefits compared to other oil crops like soybean and rapeseeds cultivation processes for biofuels. However, the high impacts from climate change potentials, acidification/eutrophication, etc., directly or indirectly affect the society negatively. Moreover, the competition of land for food crops may arise between biofuels and global food production leading to high prices of food and scarcity (food insecurity). The cultivation of oil palm biomass for biofuels are reported to have few negative social impacts on most rural communities and in some situations, positive shift in income is achieved (McCarthy 2010). The RSPO is currently working its way out to promote sustainable land use for oil palm cultivation. Primary and secondary forests are now out of focus for the oil palm industry especially in Malaysia and Indonesia but the adoption of peat lands and abandoned lands also has their assigned sustainability principles and criteria as discussed in Chap. 4, Appendix E and Appendix F. The sole production of biofuels (not considering the agriculture of the feedstocks) may not have great impacts on the society as compared to the feedstock production. The sustainability of one production chain may lead to sustainable development at the end of the whole production chain hence the need to concentrate on feedstock production for improved biofuels production. In this chapter, the common and major social impacts associated with palm biofuels production are discussed and possible sustainability measures are recommended.

Sustainable development for the palm biofuel industry cannot be realized if policy implementation programs and initiatives are not enforced by the government or nongovernmental agencies though in principle, they are not easy to achieve. In reality, the selection of a particular policy plan in relation to a specific biofuel project may often downplay the achievement of one policy over the other (Van der Horst 2005). The European Union, the United States of America as well as few countries in Asia (e.g., Malaysia) are promoting the production and consumption of biofuels via legislation and formal directives. Many policy goals have been set for sustainable biofuels production which include the minimization of

greenhouse gas (GHG) emissions, diversification of feedstock supply sources, enhancement of transport fuels decarbonization, etc. This chapter will also discuss the various policy goals set by various countries especially Malaysia and Indonesia toward sustainable palm biofuels production and consumption.

There are some few challenges facing the oil palm industry as well as the legislative bodies in achieving sustainable development in terms of social and policy implementation initiatives though oil palm productivity and cost are better compared to all other feedstocks (except algae) for biofuels production. The European Union (EU) and other regions of the world now import palm feedstocks especially palm oil in large quantities for conversion into biofuels (see [Chap. 4](#)) due to the promotion of sustainable palm oil production by the RSPO supported by policy initiatives like government subsidies and incentives on biofuels production.

Oil palm production provides many social benefits to the local folks through income addition, poverty alleviation, employment opportunities, infrastructure improvement, incentives from governments, etc. In Malaysia for instance, between 1980 and 2007, the export value of palm oil and its derivatives increased by approximately 61 % (to US\$13.8 billion) while in Indonesia, it was about US\$7.9 billion (World Bank [2009](#)). Palm oil was their lead foreign exchange earner with wide margin compared to their crude petroleum and other cash crops. However, the potential social effects to the holders and the society would be numerous and detrimental if care is not taken. Most smallholders of oil palm plantations easily loose their lands to the government or big private companies without adequate compensation and these losers are denied of mixed livelihood policies like incentives.

As environmental sustainability and economic sustainability are concerned with natural environment safety and constant financial growth, respectively, social and political sustainability are also associated with human elements and the society at large. Social-political developmental issues for sustainability concerned with palm biofuels production are discussed in this chapter.

8.2 The Concepts of Social Sustainability

Social sustainability is a dimension of sustainable development which may be independent but equally important as the economic, environmental, or thermodynamic sustainability dimensions. Presently, social sustainability is treated as a dependent component of environmental politics, and social science and policy researches have developed various social goals, strategies, and measurements with negligible reference to social sustainability (Metzner [2000](#)).

Social sustainability is an aspect of sustainable development which encircles human rights, labor rights and social justice so that the future generations would have fair access to natural resources. In as much as the future generations enjoy the naturalness of resources maintained by the current generation, there must be intra-generational equity where the current generation also access the social resources within their generation. The Interorganizational Committee on Guidelines and

Principles (ICGP) for Social Impact Assessment defines social impacts as the ‘consequences to human populations of any public or private actions that alter the way in which people live, work, play, relate to one another, organize their needs and cope as members of the society’ (ICGP 2003). Social sustainability criteria are focused on the effects of individual’s attitudes, actions, and behaviors and they may include diversity, employee relations, labor rights, governance, occupational safety, etc. The main idea of a socially sustainable community is not to end consumption but to minimize it to some extent thus luxury or wealth may not be the ultimate goal. A social sustaining system aims at taking risks in transforming resources into useful products that are actually needed and not that which the system can do without. If there be the need to change the current structures and ways of doing things, a social sustaining system takes up that challenge in creating a socially conducive environment for its inhabitants.

Social sustainability has three components namely development, bridge, and maintenance social sustainability (Vallance et al. 2011). *Development social sustainability* aims at meeting basic needs for inter- and intra-generational equity while *bridge social sustainability* aims at changing behavior and attitudes to achieve the biophysical environmental goals. *Maintenance social sustainability* deals with issues pertaining to social acceptance.

Social sustainability criteria as outlined by Hans-Boeckler Foundation (2001) include (1) satisfaction of basic needs (2) self-determined lifestyle covering means of employment (3) equal opportunities to take part in a democratic society (4) reliable social security system (5) social innovation and structuring of employment types. Some criteria of economic sustainability such as the satisfaction of the society in terms of material needs as well as stable employment, social security, fair distribution of burdens between generations have been interspersed with social sustainability criteria. Table 8.1 summarizes the general guidelines for social sustainability of a system.

The selection of social sustainability criteria and indicators must depict practical standards and practices that are comprehensive, credible, and policy-supportive. The concepts of social sustainability are mostly hidden within the indicators for socio-political sustainability. Social sustainability as defined by Littig and Grießler (2005) is the quality of a society. It describes the relationship between nature and the society such that the related institutional and ecological arrangements gratify the sets of human needs in order to maintain social justice and human dignity for a long period of time. In a situation where the connection between resource use and the society is not long lasting, there would be urgent need to reorient the economy, political, and the cultural needs to meet the principles for sustainability. However, the alteration of socio-ecological structures for social sustainability is not easily estimated and the results of these social change uncertainties would be detrimental on the society when the indicators are not chosen carefully (Becker et al. 1999).

According to Littig and Grießler (2005), three basic indicators can be used to assess the social dimensions of sustainability. The first indicator deals with the contentment of basic needs to obtain good quality of life. In a social sustaining

Table 8.1 General criteria and indicators for social sustainability

Social sustainability criteria	Social sustainability indicator
1. Social resources	– Average time spent for voluntary activities such as communal labor, politics, etc
2. Basic needs	– Population with life expectancy not exceeding 60 years – Insufficient reading and writing capabilities (functional analphabetism) – Degree of long term unemployment – Percent relative poverty, i.e., incomes below 50 % of the national mean income
3. Equal opportunities	– Gini-coefficient of income distribution – Number of women in parliament, leadership in administration, management in science, and engineering jobs, etc – Labor and human rights
4. Participation	– Weighted voter turnout and engagement in other institutionalized forms of participation
5. Sustaining oneself	– Long-term unemployment rate, extended unemployment rate
6. Cultural diversity	– Support for developing, sustaining, and documenting broadly accessible and comprehensive cultural lives in pluralistic diversity by culture, education, and research politics

Source Kopfmüller et al. (2000)

community, the basic needs of the people such as education, employment, health, shelter, food, security, entertainment, etc., must be adequately supplied. When all these are achieved, then social justice and coherence which deal with equal opportunities in education, gender equality, etc., come into play. Social coherence specifically aims for the inclusion or integration of social networks into measurement for solidarity and tolerance. Though it would be a good thing to incorporate all these social sustainability criteria into policy making, they do not easily happen. Meanwhile the major aim of these criteria are to monitor important policies and their implementation procedures.

8.3 RSPO-RED Schemes for Social Sustainability of Palm Biofuels

In April, 2009, the European Parliament and Council adopted the a new Renewable Energy Directive (RED) (Directive 2009/28/EC) which serves as directions in promoting the use of renewable energy with the hope of achieving a minimum of 10 % share of the total energy mix in the EU by 2020. Under this directive, targets for minimum ratio of biofuels to fossil fuels on the transportation sectors especially were set. The Directive 2009/28/EC aims to safeguard the use of only sustainable biofuels by setting out sustainability criteria for biofuels in relation to greenhouse gas (GHG) savings, high carbon stock, biodiversity and land use as well as other best management practices.

The certified sustainable palm oil (CSPO) completely fits as a sustainable feedstock for biofuels production under the RED scheme. For example, the RSPO addresses many social sustainability criteria which are missing in the RED criteria. In 2010, the Roundtable on sustainable palm oil (RSPO) came into agreement (which was finally approved in November, 2012) with the EU-RED (forming the RSPO-RED scheme) for the supply and purchase of RSPO CSPO products for biofuels production in the EU. The collaboration of the RSPO and RED would give RSPO members the opportunity of easily accessing the EU market for biofuels.

The RSPO-RED scheme consists of clearly laid down extra principles and criteria (from RED and RSPO) required for not only social sustainability but also the other aspects of sustainability. Though all biofuels irrespective of the feedstock location would be allowed to be on the market, only those that meet the criteria of the RED would be part of the 2020 renewable energy target and would be eligible for financial support. The commission of RED delivers bi-annual reports (which began in 2012) to the European Parliament and the council on the impacts of biofuels on social sustainability of all parties involved in the development stages of the biofuels of concern. These reports encompass the availability of cost effective foodstuffs for the indigenous people as well as the respect of land use rights (European Commission 2009). These bi-annual reports are supposed to depict the conventions of the International Labor Organization (ILO) which include forced or compulsory labor, rights to organize and bargain collectively, freedom of association and rights protection, men and women equality, minimum criteria for appointments for employment, child labor, etc.

These additional guidelines are optional for RSPO members¹ but would be beneficial in the economic sense if the palm oil mainly is produced for biofuels. Although, the RSPO does not determine the share of palm oil for food, fuel, or any other purposes, the implementation of its principles and criteria are totally ensured for sustainable palm oil production. The RSPO social criteria for sustainable palm production are more focused on:

- Conflict avoidance on land use issues,
- Legal conformity by every individual in the palm oil supply chain,
- Financial security of workers especially smallholders,
- Environmental health protection of workers and industry's neighborhood,
- Reverence for Land and labor right,
- Compliance of national and International legislation on land use planning.

¹ Most RSPO members produce palm oil for edible uses thus the criteria set for palm biofuels may not include these members.

8.4 Factors Affecting the Social Sustainability of Palm Biofuels Production

Due to the intensive policy supports from national and international agents, most developing countries are aiming high in promoting the production and consumption of biofuels. In as much as these may help mitigate climate change, there are more room for improvement so as to achieve social sustainability. There are more room for improvement so as to achieve social sustainability. An internal policy for biofuels can reduce the supply of equally beneficial commodities through which the society could be affected negatively. The cultivation of biofuel feedstocks can contribute to the loss of farming lands belonging to peasant farmers, demolition of educational and health facilities though it may have its own benefits to the local communities. Depending on the type of feedstock cultivated as well as the location for agriculture, the pros and cons could balance. However, there is the need to address the main social issues affecting the social sustainability of biofuel production. Biofuels in their current states are economically not viable and they cannot help the rural people to get cheap access to vehicles to neighboring towns and cities easily though this could have been a plus for the social sustainability of biofuel establishment in developing countries.

A system is termed socially sustainable when the processes, activities, and services that go on within and around its neighborhood completely and actively support the tendency of the current and future generations to have healthy and livable communities. In other words, a socially sustainable community is equitable, diverse, democratic, and provide a good quality of life for all (Koning 2001). This is not only attributed to the impacts from the system in operation but also the impacts of the products on the society.

The palm biofuels industry may affect the community in one way or the other with its operation and management practices as well as its products. Within the domain of the oil palm biofuels industry, there are many opportunities available to improve the subsystems within the industry for social (or societal) development. The operations and services within the palm biofuel industry must improve the quality of lives of its workers and neighboring communities. The main drivers of social sustainability for the palm biofuel industry are the agents like employers and managers of the industry who take decisions and implement them to cause changes through laid down principles. However, there are other agents like employees who may not adhere to these principles just for their benefits. For instance, smallholders of palm plantation may tend to use certain farming practices for their benefits (though those practices may not be the best) in the absence of the supervisory body that sets up the appropriate farming criteria to ensure social sustainability.

One major factor that affects the social sustainability of palm biofuel production is equity. According to Stren and Mario (2000), equity can never be eliminated from the principles of social sustainability where the extent to which inequality and social discontinuity are minimized. Without equity, the ecosystem would be an uncomfortable place for living beings as clean production and consumption

may be for only the rich while the poor also make use of their poverty status to adopt irresponsible production and consumption practices that may eventually harm the environment. In order to ensure social sustainability for the oil palm industry, workers, and the plantation's neighborhood must have equitable access to necessary resources as well as the inclusion of workers in decision making. Lack of equity and social justice in the palm biofuels industry may result in irreversible damages due to war, corruption, and crime acts which would further avert the benefits that natural resources bring to man. Social justice includes justice pertaining to dispensation of income and quality of life and participation in society (Lamer 2004). The palm biofuel industry could be more socially sustainable when issues relating to equity and social justice are addressed well. The poor and rich must be treated equally in the industry. The rights of women and children must not be infringed upon but based on their weakness.

Conflict resolutions are usually carried out by the stakeholders of the oil palm biofuel industry which involve growers, millers, refiners, and biofuel producers. These group may serve as spokespersons for the industry at any point in time especially when the highest authority like ministerial officials are involved. Normally, these stakeholders decide on appropriate design systems for biofuels production that may avoid adverse effects on the environment, economy, and society.

In sum, social sustainability could be achieved by the palm biofuel industry through transparency in acquiring lands and assets for feedstock (oil palm biomass) cultivation as well as monitoring the implementation of the principles and criteria laid down to be followed by the stakeholders for social sustainability.

8.4.1 Employment and Conditions of Service for Workers

In Indonesia and Malaysia for instance, oil palm agriculture contributes greatly to their economy in terms of revenues and employment or job opportunities (Basiron 2007; Feintrenie et al. 2010). During oil palm cultivation, field operations like harvesting, collection of fresh fruit bunches, etc., are labor intensive thus make use of many workers. In view of this, Malaysia's oil palm industry was able increase its intake of plantation and mill workers (which include foreigners from Indonesia, Thailand, Bangladesh, etc.) from about 92,000 in 1980 to about 570,000 in 2009 (Wahid et al. 2010). Presently, over 3 million jobs have been created by the palm oil industry in Malaysia contributing to the economic growth of the nation (Wahid et al. 2010). However, though the involved local people are supposed to benefit, there are many instances where these benefits are accrued to only those who have certain levels of skills and experience which eventually render most of the rural people jobless. In some other instances, large-scale production of palm oil for biofuel may provide a net gain involving rural communities in terms of job creation and income benefits only when they have official titles on their lands.

Since the oil palm is the top produced and consumed vegetable oil in the world presently, the high demand for it create room for expansion thus a source of

employment for many people in the major cultivating areas especially in Malaysia and Indonesia. For instance, the largest palm oil company in Malaysia, the Federal Land Development Authority (FELDA) Palm Industries Sdn. Bhd. (FPI) with its 720,000 ha of oil palm plantation, was able to help about 112,635 families to resettle as a result of employment given to them (Ahmad Tarmizi 2008). Due to these job opportunities offered to these local folks, their lives were upgraded in terms of finance, education, etc. Rural communities of oil palm cultivation countries depend on peasant farming for their livelihoods. For this area of subsistence farming, oil palm cultivation was more than 250 times (WWI 2006) which implies that palm oil production was a major employment for these rural folks mostly in Indonesia and Malaysia.

The oil palm plantation in Indonesia alone employed about 1.7–3 million workers who also engage in palm oil milling activities in 2005 (Wakker 2005). In 2010, as a result of palm biofuels production, about 3.6 million jobs were created in rural areas of Indonesia which helped to reduce poverty by about 16 % in the country (Oxfam's biofuel policy advisor 2008; Dillon et al. 2008; Sheil et al. 2009). However, there are still over 30 million unemployed rural folks in Indonesia (World Bank 2009). Though the smallholders in the local communities are better off with these kind of jobs that the oil palm plantation give them, the presence of big companies giving them empty promises for more better jobs have rendered over 50 % of the rural folks unhappy (Sheil et al. 2009). On the other hand, there are some few cases where the oil palm companies come to the rural communities with their labor force whom have been trained to take up the plantation practices leaving the local people jobless as their lands they mostly depend on are taken away.

Though smallholders in Malaysia and Indonesia carry the greater share of oil palm and palm oil production capacities, their workers are the least beneficiaries in terms of financial gains. The stages for palm biofuels production where many workers needed are in the plantation and palm oil mills. The palm oil refining and biofuels production stages themselves are mostly automated and do not need many workers to manage the processes.

Due to expansion of the oil palm industry, big oil palm industries impose social stresses on the local communities that mandate them to migrate from their smallholding plantations to urban areas or employ them with harsh working conditions (Marti 2008). There could be situations that most of these local people may end up with small wages, violation of their rights, etc. (Marti 2008). In Malaysia for instance, workers in the plantation are paid about US\$3–5 per day which is very low (World Bank 2009). Workers are allowed to work long hours in the sun for menial pay but still continue to work in the plantation because they have no job options hence continue to stay in these harsh working conditions (Marti 2008; Colchester 2010).

Oil palms that are cultivated on industrial scale have low jobs per hectare of cultivated land due to improved methods of agriculture for sustainable development. For instance in Malaysia, due to the RSPO certification requiring responsible farming practices, for every 12 ha of oil palm cultivated land, one person is

employed compared to the situation in Indonesia where employment rate is high (Barlow et al. 2003).

In the past, almost 50% of the total workers in the oil palm plantation in Malaysia and Indonesia were women who mostly engaged in fertilizer and pesticides applications in the plantation. These women were taken away from joblessness which eventually improved their conditions of living. Nowadays, the rate of employment in the oil palm industry has increased though there are still more room for improvement. Most of the workers in the plantation who were illiterates and poor have been given better opportunities in the oil palm industry for better living. Some employees of these workers especially the women mostly provide them with housing and other incentives which make them remain in the industry. Though the oil palm industry has not contributed 100% to socio-economic impacts of neighbouring communities, it has done better in most areas of social and economic endeavours for sustainable development.

Another challenging social issue that could affect workers in oil palm biofuels industry is the lack of training programmes for workers. In the big companies, the workers who are involved in pesticides and fertilizers applications do not know the kind of chemicals they work with and in these cases, the managers could help fund their education for sustainable production. the health of the industry's workers must be carefully catered for in order to improve the efficiency of the workers for sustainable biofuel production.

Formerly, most of the workers in the oil palm industry suffered from acute and chronic sicknesses like respiratory disorders due to the use of chemical fertilizers and pesticides. However, currently, the managers have helped improved the health conditions of almost all the workers. For improved socio-economic sustainability for the oil palm biofuel industry, there must be the need for policy interventions to offset some of the major problems pertaining to the conditions of services for workers in the oil palm plantation and mills especially. In order to improve upon labour conditions in the oil palm biofuel industry, there must be the need to revisit and evaluate labour conditions to improve the financial, health and general lives of the workers in the industry.

8.4.2 Assets Rights and Governance

Large-scale palm biofuel production may have negative impacts on resource access especially when the industry keeps expanding. Land conflicts have been one of the major challenges affecting the oil palm industry. Disagreements and conflicts on land issues occur between smallholders, local communities, indigenous people, private companies, and sometimes the government. In Indonesia, the year 2010 alone recorded about 630–3,500 land dispute cases between big oil palm companies and smallholders (Rist et al. 2010) which in fact were disturbing. Lack of equity and transparency in land and other resource sharing contributed to this high number of conflicts (Marti 2008; Rist et al. 2010). Again, the inconsistency of

the laws which were unable to recognize and respect the customary rights to land resulted in land conflicts. Oil palm industry has not been the only industry to experience this. Soybean industry in the USA has been experiencing these same situations which have affected a lot of indigenous people (Cronkleton et al. 2009).

Rural folks of palm oil producing countries have always been the losers when it comes to loss of land and other resources during new plantations and expansions (Rist et al. 2010). Large private companies and government institutions involved in oil palm production usually impose their plantations on the smallholders and rural settlers who own the lands which eventually result in loss of livelihood for the people in these rural communities (Zen et al. 2005). In some few cases, palm oil companies have tried using unauthorized and violent strategies to take the lands of the indigenous communities for oil palm expansion (Rist et al. 2010; Zen et al. 2005). These are bound to happen at any time without much notice to the rural people but in the name of national development, they are easily displaced leaving them homeless. Although proper compensation for lost of assets during oil palm establishment could lead to better lives of the victims, they are mostly not considered and implemented and this result in inequitable outcomes. All these problems about land arise because most of the smallholders do not have titles to land (and conversion of traditional land claims into official titles is near impossible) which eventually enfeeble their negotiations abilities (Colchester et al. 2006; Colchester and Chao 2011). Apart from this scenario, there exists land conflicts between individual holders, communities, and private companies involved in oil palm production. Mostly, the smallholders may trade their land quota to the government or big private companies for plasma areas which are usually 1–3 % of the total land area traded (Colchester et al. 2006; De Schutter 2009; German et al. 2011). In some instances, the smallholders may place part of their land as collateral for loans from the bigger companies and at the end, they stand to lose (De Schutter 2009; German et al. 2011). The absence of clear agreements between investors and smallholders seriously affect the social lives of the oil palm smallholders especially in the rural areas.

Though the oil palm is found to be productive, the production, processing, and marketing of palm biofuels affect the resource rights through the acquisition of titled or untitled lands, and other assets (Cotula et al. 2008; German et al. 2011). These assets rights may again be affected by the types of restrictions that are placed on existing rights based on the agreements made between palm biofuel investors and smallholders. Though there are a number of laid down principles governing land rights, they are normally not adhered to by oil palm companies.

Among the social sustainability principles, set by the RSPO-RED is to recognize and respect local land rights. Social sustainability indicators for the implementation of these principles include (1) the identification and regular documentation of all existing ownership of land and resource use rights (2) equitable compensation for all rights taken (3) fair negotiations between investors, smallholders, government, and other affected land users for peaceful transfer of land rights (4) establishment of a trustworthy medium through which individual grievances can be addressed and settled amicably.

The international human rights law endorses the right to self-determination. An individual has his/her freedom to develop his/her social, economic, and cultural talents without interference from outside parties (De Schutter 2009). Thus, the rights of an individual to use his/her property in a way he wishes must not be jeopardized by a higher authority. However, many communities are not consulted prior to the clearing of their lands for oil palm expansion (Colchester 2010). Some of these communities may not even know that their lands are being converted to oil palm plantations until they find heavy tracks pulling down the trees on their lands.

In order to do away with these negative social impacts which oil palm cultivation come with, there must be collaborations between the government and the big oil palm industries to enact laws to govern assets rights when it comes to oil palm cultivation. Land rights levied on local smallholders would allow them to prevent the expansion of oil palm plantations by the big industries in areas which are unauthorized. Again, land transfer and debts contracts that are signed between smallholders and big companies must be clear and fair. The RSPO principles for social sustainability of oil palm cultivation must be enforced and periodically assessed to ensure that those principles are adhered to by involving bodies.

Moreover, smallholders can form cooperatives or groups that could help negotiate deals with the big oil palm industries on assets rights. These groups could raise their concerns to the governments and the RSPO upon any conflicts pertaining to land rights. When smallholders are properly cared for and their developments become prime issues for the oil palm industry, there could be tremendous growth in the industry than big companies buying lands from them for expansion. Conflicts between smallholders and big companies of oil palm cultivation over land issues must be settled amicably through intermediate groups comprising government officials and other neutral bodies.

Palm biofuels production may not require large area of land for operation but as sustainability principles suggests siting closer to the palm oil mills and the plantation, there could be conflicts related to land rights. The proper route to acquiring land for constructing the plant must be followed in order to do away with any conflicts which would eventually affect the social sustainability of the oil palm biofuels industry.

Koczberski and Curry (2005) have suggested that land conflicts avoidance could be achieved by formulating innovatory and sustainable smallholder policies like intercropping. In this case, the oil palm industry's aim to stop the production of lands belonging to smallholders would be a success story. Again, to help solve conflict relating to land ownership, the Ministries of Forestry, Agriculture and Land Use Planning must produce options to strengthen customary rights in all countries producing palm oil for biofuels and food.

8.4.3 Impacts on Livelihood and Culture

The standard of living in rural communities are best assessed using sustainable livelihood approaches which considers capital in the form of human, natural, social, physical, and financial resources (Chambers and Conway 1992). Oil palm expansions have driven local land owners away from their territories where they used to farm and carry out their daily economic activities. Obidzinski et al. (2012) have concluded from their survey in oil palm production areas in Indonesia that about 47 % of the local people traded their livelihoods as a result of direct land transfer to oil palm companies. These rural people therefore have to walk over long distances to collect forest products for their domestic activities and also open up new fields for crop rotation or shifting cultivations. Local communities who depend on firewood for income had to turn to other sources of livelihood due to dwindling forest resources resulting from oil palm expansion.

One other important asset for individuals and the community is culture thus its protection, promotion, and maintenance are vital for social sustainability (mitigating conflicts and promoting peaceful and equitable changes) for the present and future communities. Although culture and societies keep changing, an abrupt alteration of their social benefits to other fields would bring scenic changes to the communities. The expansion of oil palm plantation has adverse effects on the culture and livelihoods of the rural or local people around the plantation domain. As the local people are driven away by the oil palm industries for oil palm expansion, the traditional customs, values and languages of the people tend to wipe out as they move to different localities.

One major challenge faced by the local communities closer to the oil palm plantation is the development of palm oil mills closer to the plantations which also take away from them their land and other livelihood tactics. Rural people mostly have their entertainment activities outside their homes near the plantations but due to the existence of additional structures for palm oil milling, their places of entertainments are taken away from them. This leave deep vacancies that are mostly filled with boredom as their cultural means of socialization are nibbed in the bud.

Since the forest and land are the places for obtaining knowledge and storing cultural memories, they must be protected and handled with care. Nonetheless, the oil palm plantation expansions has contributed to the loss of gardens and some memorable cultural or ancestral sites (Belcher et al. 2004) that serve as recreational resources for the rural people. The rituals and other cultural activities that were part of the farming practices of the local communities are lost. During the lost of these rich cultures, some basic beneficial traditional subsistence farming are also lost leading to market fluctuations of palm oil prices. In order to maintain the communities' rich cultures for social sustainability of oil palm production, leaders of smallholder associations must put the interests of the communities first before the oil palm companies. On the other hand, the establishment of palm biofuel production plants would be a plus for the local community through the existence of social amenities and infrastructure, tourist sites and good market opportunities.

8.4.4 Human and Labor Rights

There has been many cases of human rights abuse by oil palm companies during land acquisition and development which always go against the smallholders (Marti 2008). The production of oil palm biomass for biofuels production requires human energy (or labor force) for most of the management practices to be carried out. Thus, human and labor rights can equally be infringed upon during the operations of palm oil production. Human rights such as rights to water, work, culture, health, possessions, etc., are mostly denied in many communities that involve the production of palm oil (Colchester 2010; Marti 2008).

The operations of palm biofuel production systems may subvert both domestic and international labor laws based on the type of practices and criteria used to employ the workers to operate the system. In a socially sustainable system where labor and human rights are protected and promoted, workers live improved lives. For instance, according to the conventions of the International Labor Organization (ILO), labor rights include the freedom of association and collective bargaining, avoidance of forced or compulsory labor, avoidance of discrimination with regards to employment, abolishing of child labor, etc. (ILO 1998).

All workers in a company or institution are given the rights to obtain the correct salary at appropriate periods based on human rights laws commissioned by the nation. However, most companies may break this regulation by paying their workers less than the minimum wage which eventually leads to labor conflicts. This situation may be rampant at places where casual workers who have less legal protection than permanent employees are many especially in the plantation and mills (Marti 2008). The production of palm biofuels in Indonesia is projected to provide over 2.5 million jobs in the next couple of years to come (Cassman and Liska 2007). However, in circumstances where expansion of biofuel systems are made, land tenure becomes poorly defined and the labor rights are violated.

Child labor has been one of the major negative social impacts associated with palm oil production. Through the desire for children in the rural communities involved in palm oil production to learn a trade or earn income to help their parents, they resort to work in the palm oil industry. In most cases, the location of the rural communities who are into palm oil production are too far from accessible schools thus making the children involve in plantation companies. In RSPO guidelines, criterion 6.7 clearly states the involvement of children in dangerous and strenuous working condition in the palm oil industry. Children are supposed to help their parents in their farms under the parent's supervision and this activity should not interfere with the education of the child (RSPO 2007).

8.4.5 Food Security

Palm biofuels are produced from both first and second generation palm feedstocks (see [Chap. 4](#)). However, the production stages of oil palm biomass as major feedstock for palm biofuels production is inevitable. It is currently debated that biofuels from palm oil result in food insecurity as the feedstock is the top edible vegetable oil in the world. Nevertheless, second generation biofuels sourced from nonedible resources from oil palm biomass must be cultivated through the same means as first generation palm feedstocks thus the need to address the issue of food insecurity based on the considerations of first and second generation palm feedstocks.

Food insecurity resulting from the cultivation of oil palm biomass has caused an increase in food crops prices. There is increased demand for biofuels feedstocks and this has negatively affected the supply demand imbalances for food substitutes (Rosegrant 2008). In Malaysia and Indonesia for example, most of the food crops peasant farmers in the rural areas have been dislocated due to oil palm expansion. Most of these local people were employed in palm oil production for biofuels hence the productive resources like land for food crops have jeopardized their livelihood. Customary and other food croplands are mostly displaced during the cultivation of oil palm for biofuel production and the effects of these land use change are detrimental to food security.

Malaysia's palm oil is mostly exported to Europe and other countries in Asia for food and biofuels applications. In situations like these where the demand for palm oil keep rising, vegetable oil for food in Malaysia may reduce in capacity and this could bring about food insecurity. Thus, there must be the need to adopt strategies and principles to minimize the instability of supply of palm oil by preventing large volumes of food when other possible markets are available (FAO 2012). This implies that peasant farmers who are not involved in oil palm plantation must be protected by the government so that oil palm companies would not drive them away for expansion. Due to the high productivity of the oil palm, these challenges pertaining to food insecurity may not be harsh compared to other feedstocks like rapeseed, soybean, sunflower, corn, etc. In the USA for instance, corn and soybean production for biofuels were found to contribute high food prices to some degree in 2008 (Mitchell 2008; Baier et al. 2009). However, the impacts of biofuels production on food security may differ from one location and conditions to the other (Gallagher 2008). Poor people in the rural areas may experience long-term effects from the land use change regarding oil palm production. Poverty rate may continue to rise and if the government does not intervene to alleviate these effects, palm oil production may continue to affect the social security of the local communities.

Biofuels companies and investors are mandated by the United Nations' (UN) special Rapporteur on the 'right to food' to stick to a minimum fraction of energy crops or feedstocks that are sold on the local market (De Schutter 2009). Research and development are needed in order to make out appropriate feedstock type, pretreatment processes as well as processing structures that would fit into the needs and values of a particular community where the biofuel plant is to be constructed.

8.5 Regulatory and Policy Initiatives for Sustainable Palm Biofuels Production

Some major threats to sustainable biofuels development at the governmental, international, and local levels include the lack of ineffective policies, government structures, and management systems that are associated with environmental, economic, and social performances. These challenges are mostly offset when there is a strong private/public partnership and effective laws and regulations which are enforced through appropriate media.

From 2010 to 2020, Indonesia intends to expand their oil palm plantations on marginal or 'idle' lands for an estimated area of about 3–7 million ha for food and biofuels (Hallam 2009; Gingold 2010). Due to oil palm expansion for food and biofuels, major palm oil producing countries have started enacting and implementing policies and regulations which aim to move the oil palm industries toward sustainable development through incentives and subsidies (Hallam 2009).

Policies and regulations are instruments that provide and direct the allocations and implementations of incentives and boundaries for programs and practices. While policies create and help boost up incentives, regulations put in place the constraints and parameters to ensure that programs and practices pertaining to biofuel production lead to sustainable development. Biofuels policies and regulations are made purposely to cover some tools such as import tariffs, mandates and targets, subsidies on production and consumption, biofuels excise exemptions, infrastructure, research and development, etc., based on set sustainability criteria for a particular biofuel (Bauen et al. 2009). Biofuel policies may also target agriculture, land use, labor, trade, and other related policies. Biofuels regulations and policies may be independent on biofuels legislation for an economy.

Malaysia being the world second largest producer and leading exporter of palm oil began its biofuel policies in August, 2005 with the enactment of the National Biofuel Policy (NBP) in 2006 (MPOB 2010). These policies aim to minimize the dependency on other forms of imported oils and increase the production of palm oil while sustainability remains the core principle. If all the stakeholders in oil palm producing countries in the world implement the regulations of the NBP, there would be improved energy supply and clean environment hence better living conditions for the involving local communities (Yatim 2009).

The NBP of Malaysia has five main strategies for implementation which includes palm biofuels for:

- Cleaner environment,
- Export,
- Industry,
- Transport,
- Technologies.

The NBP considers the short-, medium-, and long-term development and sustainable supply and consumption of palm biofuels (mostly biodiesel) in order for

Malaysia to meet the goals of the world's renewable energy. The overall benefits of the NBP would stretch out to facilitate the well-being of all the stakeholders in the oil palm industry through steady and remunerative prices (Mamat 2009). The Malaysian NBP's objectives and initiatives are in accordance with the aims of the United Nations Framework Convention on Climate Change (UNFCCC) and the Ministry of Plantation Industries and Commodities of Malaysia lead it since 2006.

In the short-term basis of NBP implementation strategies, the standard specifications for Malaysian palm biofuels are to be established and awareness programs are to be carried out. Selections of palm biofuel pumping stations as well as various trials of B5 palm biofuels on selected vehicles and industries are carried out during the short-term implementation stage by the MPOB in order to ascertain the degree of acceptance of the biofuel.

The medium-term implementation strategy centers more on the establishment of palm biofuels standards for both domestic and export purposes. During this stage, intensive trial tests on engines and efforts to get the engine manufacturers to expand their warranties to the use of B5 palm biofuels. The legislation to mandate the use of B5 palm biofuels would therefore be passed and enforced in the medium-term implementation stage of the NBP.

The long-term implementation strategy of the NBP would help save foreign exchange, increase the demand for palm oil, save the environment, facilitate the efficient use of land and other resources for sustainable oil palm development, and reduce the impacts of increased petroleum prices on the economy.

Palm oil producing countries like Indonesia, Malaysia, Colombia, etc., have been known to be major contributors to biodiversity loss due to land clearing for oil palm cultivation. These and other several issues regarding environmental degradation have been the ultimate concern of the world's oil palm industry and this has facilitated the enactment of regulations and policies to promote sustainable development. The main aim of the strategy for 'cleaner environment' is to promote and maintain ambient air quality, reduce the dependency on fossil fuels, minimize greenhouse gas (GHG) emissions, and other particulate matter into the environment during the production and use of palm biofuels (López-Moreno et al. 2008). However, there are policies guiding the amount of palm oil used for biofuels in order not to jeopardize the availability of palm oil for edible applications. The NBP of Malaysia mandates a maximum of 6 million tons of palm oil for biofuels production annually (Schott 2009; MPOB 2010). For forest and biodiversity conservation, the Malaysian NBP targets about 56 % of their forested lands to remain forest without conversion to oil palm plantations. These policies are strictly monitored and implementation strategies are carried out with supports from the Malaysian Palm Oil Wildlife Conservation Fund (MPOWCF) patrol teams who ensure that forest areas around oil palm plantations are protected. Again, protection of asset rights has been incorporated into the regulations and laws so that local communities are not deprived of their land ownerships when it comes to oil palm plantation expansions by other stakeholders (Wahid et al. 2010). Since 1997, the government has banned the clearing of forests and vegetation for oil palm expansions using fires (López-Moreno et al. 2008). This law has helped reduce the

pollution caused by smoke and other greenhouse gases from the burning of bushes. Though the NBP of Malaysia limits the clearing of food crop lands for oil palm cultivation to about 25 %, the European Union (EU) continues to raise concerns over the environmental sustainability of palm biofuel feedstocks that are exported to their territory (Hoh 2009; López-Moreno et al. 2008). Meanwhile, as already discussed in Chap. 4, Malaysia and Indonesia would not have to destroy their forests during oil palm expansion for palm biofuels production.

The policies on palm biofuels for export started to be implemented in Malaysia in 2006 in which it was mandated for instance to consume B5 palm biodiesel by the end of 2008 though it was rescheduled for 2009 due to high oil prices (Hoh 2009; Mamat 2009). Policies on compulsory consumption of B5 palm biodiesel for sea and land transportations by 2010 are also included in the biofuel policies. In accordance with these policies, Malaysia was able to produce and consume approximately 34 tons of B5 palm biodiesel in 2009 (Mamat 2009) as a test implementation using selected vehicles. The current goal in Malaysia concerning B5 palm biodiesel use is to replace over 500,000 tons of petroleum diesel every month which could reduce nearly RM 1 billion in foreign exchange (Yatim 2009).

Another strategy thrust for the implementation of palm biofuels as outlined in the Malaysian NBP is the use of B5 palm biofuels by the industries. Though the palm oil mills are found to be self-sufficient in terms of energy use, most of them still use fossil-based energy for their operations. The NBP has therefore mandated the use of even higher blends of palm biofuels by the industries in the countries especially the oil palm industry in order to reduce GHG emissions.

The NBP strategic thrust did not leave out policies on research, development, and commercialization of palm biofuel technologies which were to be funded by the government and other private organizations. Again, technology transfer in the form of seminars, conferences, workshops, etc., is funded by the government in order to promote sustainable production and consumption of palm biofuels in Malaysia. The Malaysia Palm Oil Board (MPOB), the Industrial Research Institute of Malaysia (SIRIM), and several other institutions including universities, have carried out the research and development of palm biofuels and a new technology for producing palm biodiesel (called Envo-diesel) which is mostly blended with petroleum diesel has evolved. This B5 palm biofuel blend specification has been accredited by the Malaysia's department of standards and coded under the section Petroleum and Gas (MS 2007:2007 P) (MPOB 2010).

From 2004 to 2006, Malaysian government allocated about US\$26.8 million in the form of loans, grants, and Investment tax allowances (ITA) that are given to industries and institutions for research and development in support of palm biofuel industry (Abdullah et al. 2009; Lopez and Laan 2008). Many biodiesel production companies have benefited from these government incentives but the actual gains cannot be estimated. However, Lopez and Laan (2008) again reports that though incentives are given to palm biofuel industries in Malaysia, the government is yet to give subsidies for palm biofuel production and consumption. Any palm biofuel industry which has the ITA status is permitted tax exemption on at least 70 % of its statutory income for 5 years (Biofuel Database 2007) depending on the type of

palm biofuel produced. Palm biofuel companies that are half-owned by Malaysia with export potential in palm oil are eligible for reinvestment incentives for resource-based industries (Lopez and Laan 2008). Other incentives like ‘Incentives for high technology companies’, Incentives for commercialization of research and development findings of the public sector in resource-based industries’, etc., are available for palm biofuel industries which meet certain criteria. However, palm oil industries that do not produce biofuels are not eligible for these incentives and are not exempted from taxes. For instance, a cess of US\$3.4 and 0.6 per ton of palm oil produced is supposed to be paid by oil palm growers and palm oil millers respectively to the MPOB for research and development (Chandran 2004; Hanim 2009). Again, smallholder and government land schemes are also exempted from payment. Export duties on palm oil for both food and biofuels are imposed on in order to encourage domestic palm oil production and processing. Palm oil producers in Malaysia have to pay windfall tax (based on palm oil production and not the company’s profits) any time palm oil prices rise to exceed US\$923.1 per tonne (Hanim 2010). However, smallholders who possess at least 40 ha of oil palm plantation are exempted from paying these windfall taxes.

In spite of all these subsidies and incentives given to palm biofuels industry, biofuel production from oil palm biomass is still not financially viable unless extensive subsidies are given. The price of palm oil is relatively high to be used for biofuel production as palm biodiesel for instance cost US\$0.2 per liter extra compared to petroleum diesel (Hanim 2010). Currently, petroleum diesel is highly subsidized by the government compared to palm biofuels thus cannot compete in the domestic market unless fossil fuel becomes very expensive.

From 2006 to 2010, oil palm production area in Indonesia recorded continual increase of about 2.37 million ha (Slette and Wiyono 2011) due to the supports from the government through policy implementation programs to help raise the capacity of palm biofuels in the country. Since 2006, palm biofuels especially have attracted the interest of the Indonesian government due to promotion to reduce the country’s dependency on fossil fuel (Beyond Petroleum 2010). However, the cost of subsidies on fossil fuels and their products are unattractive to the government as they take up huge financial resources that could have been used efficiently for major developments and improvement of the nation (Beaton and Lontoh 2010). For instance, in 2010, the government allocated about US\$21.9 billion for fossil fuel subsidies which formed about 15 % of what the nation spends in a year (Kaiser 2011). Accordingly, policy makers have opted for palm biofuels and other sources of renewable energy as the main strategy to reduce cost and save the environment.

The Presidential Regulation No. 5/2006 has been the key policies under the National Energy Policy (NEP) for the development of biofuels including palm-based biofuels in Indonesia. This policy mandates 2 % biofuel consumption in the country by 2010, which is to increase to 5 % by 2025. Based on the objectives of the NEP, the Indonesian Ministry of Energy and Mineral Resources (MEMR) intends to increase the production capacities of palm biofuels especially biodiesel to about 4.16 billion liters by 2025 (DESDM 2006).

In Indonesia, the strategy to keep the environment clean during palm biofuel production and use is clearly stated in their Energy and Mineral Resources Ministerial Decree No. 32/2008 whereby environmental impact assessments for all biofuels production systems are mandated on regular basis. Recently, the Indonesian Ministry of Agriculture brought up an act concerning the cultivation of oil palm on peat lands. Under this act, peat lands are supposed to be used in situations where mineral soils are unavailable and in such cases, the peat lands use must conform to the act's criteria and principles. Peat lands with depth more than 3 m whose subsoil is silica sand or acid sulfated are not supposed to be used for oil palm plantation. Also, peat lands with highly and moderately decomposed soils can be used (Winrock International 2009). Cooperation between Norway and Indonesia on GHG reduction from deforestation and forest degradation has been established which mandates in their laws that from 2011 to 2013, there should be no expansion of oil palm on forest (López-Moreno et al. 2008).

The NEP of Indonesia covers issues pertaining to trading systems, incentives, tariffs, standards, and practices for sustainable oil palm cultivation, processing and quality assurance, technology, research and development, and above all acquisition of lands for oil palm expansion.

The NEP again clearly mandates the provincial governors, district leaders, and community heads to support the establishment and development of biofuels in any form possible. However, institutions, individuals, and other corporations are not left out in the development of palm biofuels in Indonesia as outlined in the NEP.

Since 2006, based on the United States' standards (ASTM D 6751) and the European Union standard (EN 14214:2002) on biofuels, Indonesia's National Standardization Agency have approved new standards for palm biofuels like biodiesel (SNI 04-7182-2006) and bioethanol (SNI DT27-0001-2006). With these policies in place, palm biofuel companies in Indonesia began the sales of B5 and E5 palm biofuels in 2006.

To facilitate proper implementation of the NEP, additional regulation (No. 051/2006) was issued by the Indonesia's MEMR, which outlined the processes of developing biofuels production system in Indonesia that would be conducive to investors. The new regulation mandates palm biofuel companies and stakeholders to provide regular supply of the biofuel for domestic needs.

One of the incentives implemented under the NEP exempts biofuel industries from value-added tax levied on the transfer of biofuels. Other incentives are in the form of income tax reduction, government guarantee against operational losses, accelerated depreciation, and amortization (Ministry of Finance Decree No. 156/PMK.011/2009). In 2009, another regulation of the NEP (Presidential Regulation No. 45/2009) was enacted which considered a subsidy of US\$ 0.1 per liter of biofuel for all industries which produce low cost biofuels compared to petroleum diesel. The values of the subsidies were increased to US\$0.2 and US\$0.27 per liter biofuel in 2010 and 2011, respectively (The Jakarta Post 2010).

During the first year of the implementation of the NEP of Indonesia, investment in the biofuel sector was very significant with massive supports from private sectors, banks, Nongovernmental organizations, governmental institutions, etc.,

but unfortunately, the interest declined as a result of increased in palm oil prices (in 2008) and decrease in fossil fuel prices on the international market (MEMR 2006). Consequently, in 2008, the Indonesian Association of Biofuel Producers (APROBI) reported that only about 17 biodiesel companies and 5 palm oil mills were in operation which caused a decrease in overall production capacity of biofuels in the country. As a result of these constraints, the biofuel blending targets were reduced from 5 to 2.5 % though the biofuel industries are still up and coming.

Based on the Indonesia's Ministry of Agriculture's decree No. 19/Permentan/OT.140/3/2011, the Indonesian government launched the Indonesian Sustainable Palm Oil (ISPO) standard aims to help palm oil companies to achieve sustainable production. The ISPO has also come to support RSPO to improve the sustainability of oil palm and palm biofuels production and move of the Indonesia's palm oil market toward sustainable development (Paoli et al. 2010). However, many smallholders complained about the high cost of RSPO certification, which also created thick barrier for them to join the line for sustainable oil palm development (The Jakarta Post 2010). Contrary to the principles of the Roundtable on Sustainable Palm Oil (RSPO), the ISPO comprises 7 principles, 39 criteria, and 128 indicators and it covers cultivation and processing management practices, environmental monitoring, labor, social justice, economic empowerment, etc. (Dirjen 2011). The eight principles of the RSPO are outlined in Chap. 1 (Table 1.1).

In 2003, Peru adopted Law 28054 to promote a biofuels market at the national level, in line with the government's policy to develop renewable energy resources and as a strategy for poverty alleviation. A regulatory framework on biofuels was established in 2007 setting a blending mandate for ethanol and biodiesel: The blends stipulate a 7.8 % ethanol blend with gasoline starting in 2010, a 2 % biodiesel blend with diesel starting in 2009 to be phased into a 5 % biodiesel blend in 2011. Diesel is the most widely used transport fuel in Peru; the demand at 2007 was 61 Million of Barrels per day (MBD) and it is expected that at 2016 this value will reach 86 MBD. A 2 % blending mandate will require 1.4 MBD of biodiesel and a 5 % will require 3.7–4.3 MBD of biodiesel (PETROPERU 2007). The government has estimated that the production of oilseed crops in deforested lands can be used to produce the feedstock to meet the blending mandate.

8.6 Conclusion

Throughout the production chain of palm biofuels, the feedstock cultivation is found to have greater social impacts on the rural communities that are involved. Many are the challenges faced by the oil palm industry as well as the legislative bodies in achieving sustainable development in terms of social and policy implementation initiatives though oil palm productivity and cost are better compared to other feedstocks (except algae) for biofuels production. Though oil palm production provides employment for most rural people, challenges associated with land rights, food security, health, livelihoods, etc., would have greater negative

effects on the local communities if sustainable production principles are not effectively adhered to. The implementation and enforcement of effective policies and well as laws and regulations on palm oil production could help minimize the negative social impacts for sustainable palm biofuel development.

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Appendix A

Table. A.1, Table A.2, Table. A.3, Table. A.4, Table. A.5, Table. A.6, Table. A.7, Table. A.8, Table. A.9

Table A.1 Energy balance (MJ) for the production of a single oil palm seedling (Halimah et al. 2012; Schmidt 2007; Nikander2008)

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Germinated seeds	kg	0.13	33.64	4.3732
Polythene bags	kg	3.86E−03	45.57	1.76E−01
Water for irrigation	kg	2.66	0.0042	1.12E−02
Fertilizer				
<i>Nitrogen</i>	kg	9.93E−04	48.90	4.86E−02
<i>Urea</i>	kg	1.31E−03	22.50	2.95E−02
<i>P₂O₅</i>	kg	2.85E−04	17.43	4.97E−03
<i>K₂O</i>	kg	2.04E−03	10.38	2.12E−02
<i>MgO</i>	kg	4.88E−04	2.32	1.13E−03
<i>Borate</i>	kg	1.15E−04	32.27	3.71E−03
Pesticides and Herbicides				
<i>Glyphosate</i>	kg	2.74E−02	18.62	5.10E−01
<i>Furadan</i>	kg	2.05E−02	13.16	2.69E−01
<i>Paraquat</i>	kg	1.37E−01	130.00	17.81
<i>Pyrethroid</i>	kg	3.54E−06	27.21	9.63E−05
<i>Organophosphate</i>	kg	2.25E−05	–	–
<i>Dithiocarbamate</i>	kg	9.61E−05	–	–
<i>Thiocarbamate</i>	kg	1.32E−05	–	–
Labour	MJ			3.60E−03
Transportation (diesel)				
<i>Chemicals to nursery</i>	kg	5.88E−02	48.10	2.828
<i>Seedlings to plantation field</i>	kg	4.69E−03	48.10	2.26E−01
<i>Total energy input</i>	MJ			26.300
Oil palm seedlings	kg	0.69	36.04	24.868
Emissions to soil, water and air				

(continued)

Table A.1 (continued)

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
<i>Nitrogen</i>	kg	1.43E-04	48.9	6.99E-03
<i>P₂O₅</i>	kg	5.73E-05	17.43	9.98E-04
<i>Glyphosate</i>	kg	1.12E-02	18.62	2.09E-01
<i>Paraquat</i>	kg	9.34E-03	130.00	1.214
<i>Furadan</i>	kg	1.01E-02	13.16	1.33E-01
<i>NO_x</i>	kg	5.27E-03	296.00	1.559
<i>CO₂</i>	kg	1.589	32.12	51.039
<i>SO₂</i>	kg	2.11E-03	29.50	6.22E-02
<i>CO</i>	kg	0.145	10.11	1.466
<i>Total energy output</i>	<i>MJ</i>			<i>80.60</i>

Table A.2 Energy balance (MJ) for the production of 1 kg fresh fruit bunch (FFB) (Schmidt 2007; Yusoff 2007)

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Oil palm seedlings	kg	0.0035	36.04	1.26E-01
Water for irrigation	kg	522.665	0.0042	2.195
OPF for mulching	kg	9.00E-04	20.51	1.85E-02
Pesticides and herbicides				
<i>Glyphosate</i>	kg	4.41E-04	18.62	8.21E-03
<i>Pyreteroid</i>	kg	2.02E-05	27.21	5.49E-04
<i>Organophosphorus</i>	kg	5.95E-05	–	–
<i>Furadan</i>	kg	7.17E-04	13.16	9.44E-03
<i>Paraquat</i>	kg	1.68E-04	130.00	2.18E-02
Fertilizers				
<i>Nitrogen</i>	kg	6.93E-03	48.90	3.39E-01
<i>Urea</i>	kg	1.01E-02	22.50	2.27E-01
<i>P₂O₂</i>	kg	2.19E-03	17.43	3.82E-02
<i>MgO</i>	kg	3.75E-03	2.32	8.70E-03
<i>Borate</i>	kg	8.83E-04	32.27	2.85E-02
<i>K₂O</i>	kg	1.57E-02	10.38	1.63E-01
<i>Murate of potash (KCl)</i>	kg	1.08E-02	25.24	2.73E-01
<i>Ammonium nitrate</i>	kg	7.16E-04	26.37	1.89E-02
<i>Ammonium chloride</i>	kg	7.01E-04	23.00	1.61E-02
Labour	MJ	1.44E-03	–	1.44E-03
Electricity	MJ	2.97E-01	–	2.97E-01
Diesel for field establishment and maintenance	kg	9.56E-03	48.10	4.59E-01
Transportation (petroleum diesel)				

(continued)

Table A.2 (continued)

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
<i>Chemicals to plantation</i>	kg	4.94E−03	48.10	2.38E−01
<i>FFB to palm oil mill</i>	kg	7.43E−04	48.10	3.57E−02
<i>Total energy input</i>	<i>MJ</i>			<i>3.490</i>
FFB	kg	1.00	43.33	43.330
OPF	kg	3.59E−01	20.51	7.363
Emissions to soil/air/water				
<i>Pesticides and herbicides</i>	kg	8.87E−05	–	2.18E−02
<i>Fertilizers</i>	kg	1.86E−03	–	6.89E−02
<i>NO_x</i>	kg	1.10E−04	296.00	3.26E−02
<i>CO₂</i>	kg	2.62E−03	32.12	8.42E−02
<i>SO₂</i>	kg	4.32E−05	29.50	1.27E−03
<i>Others (particulate matter etc.)</i>	kg	1.78E−03	–	–
<i>Total energy output</i>	<i>MJ</i>			<i>50.902</i>

Table A.3 Energy balance (MJ) for the production of 1 kg CPO (Wicke et al.2008; Yusoff 2007; Subranamiam et al. 2004; Vijaya et al. 2010)

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Palm oil milling inputs				
FFB	kg	4.436	43.33	192.22
Electricity from CHP plant	MJ	3.13E−01	1.00	3.13E−01
Steam from CHP plant	kg	5.929	1.36	8.063
Process Water	kg	7.001	0.0042	2.94E−02
Labor	MJ	6.40E−03	–	6.40E−03
Diesel for CPO processing	kg	1.28E−04	48.10	6.16E−03
Transportation (petroleum diesel)				
<i>Chemicals to oil mill</i>	kg	7.11E−04	48.10	3.42E−02
<i>CPO to refinery</i>	kg	6.18E−03	48.10	2.97E−01
Total energy input	<i>MJ</i>			<i>200.969</i>
Palm oil milling outputs				
CPO	kg	1.000	39.40	39.400
POME	kg	2.447	21.41	52.390
EFB	kg	1.145	20.47	23.438
PPF	kg	0.763	19.22	14.665
PKN	kg	0.695	34.71	24.123
Emissions to soil, air, and water				
<i>Steam</i>	kg	5.829	1.36	7.927
<i>NO_x</i>	kg	6.26E−04	296.00	1.85E−01
<i>CO₂</i>	kg	1.276	32.12	40.985
<i>CO</i>	kg	5.52E−03	10.11	5.58E−02
<i>SO₂</i>	kg	1.91E−05	29.50	5.63E−04
<i>Particulate matter</i>	kg	1.35E−03	–	–

(continued)

Table A.3 (continued)

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
<i>Total organic carbon (TOC)</i>	kg	4.89E-05	–	–
<i>Volatile organic compounds (VOC)</i>	kg	3.84E-03	–	–
<i>Biogas from POME</i>	MJ	6.85E-02	–	6.85E-02
<i>Biochemical oxygen demand (BOD)</i>	kg	–	–	–
<i>Chemical oxygen demand (COD)</i>	kg	–	–	–
<i>Nitrates</i>	kg	8.07E-04	22.50	1.82E-02
<i>Total energy output</i>	<i>MJ</i>			203.256

Table A.4 Energy balance (MJ) for the production of 1 kg CPKO (Subranamiam 2006; Subranamiam et al. 2004; Womeni et al. 2010)

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Palm kernel oil extraction inputs				
PKN	kg	3.072	34.71	106.629
Electricity from CHP plant	MJ	1.27E-01	1.00	1.27E-01
Steam from CHP plant	kg	2.147	1.36	2.919
Process water	kg	2.840	0.0042	1.12E-02
Labour	MJ	2.59E-03	–	2.59E-03
Diesel for CPKO processing	kg	5.19E-05	48.10	2.49E-03
Transportation (petroleum diesel)				
<i>Chemicals to oil extraction unit</i>	kg	7.11E-04	48.10	3.42E-02
<i>CPKO to refinery</i>	kg	6.18E-03	48.10	2.97E-01
<i>Total energy input</i>	<i>MJ</i>			110.022
Palm kernel oil extraction outputs				
CPKO	kg	1.000	35.56	35.560
Waste water	kg	9.93E-01	21.41	21.260
PKC	kg	1.802	18.84	33.949
PKS	kg	0.336	22.14	7.439
Emissions to air and water				
<i>Steam</i>	kg	2.365	1.36	3.216
<i>NO_x</i>	kg	2.54E-04	296.00	7.52E-02
<i>CO₂</i>	kg	5.18E-01	32.12	16.638
<i>CO</i>	kg	2.24E-05	10.11	2.26E-04
<i>SO₂</i>	kg	7.75E-06	29.50	2.29E-04
<i>Particulate matter</i>	kg	5.48E-04	–	–
<i>Total organic carbon (TOC)</i>	kg	1.98E-05	–	–
<i>Volatile organic compounds (VOC)</i>	kg	1.56E-03	–	–
<i>Biogas from waste-water</i>	MJ	2.78E-02	–	2.78E-02
<i>Biochemical oxygen demand (BOD)</i>	kg	–	–	–
<i>Chemical oxygen demand (COD)</i>	kg	–	–	–
<i>Nitrates</i>	kg	3.27E-04	22.50	7.36E-03
<i>Total energy output</i>	<i>MJ</i>			118.173

Table A.5 Energy balance (MJ) for the production of 1 kg RBDPO/RBDPKO (Mortimer et al. 2010; Tan et al. 2010)

	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Palm oil refining inputs				
CPO/CPKO	kg	1.016	39.40*	35.265
Steam	kg	3.949	1.36	5.371
Process water	kg	1.05E-01	0.0042	4.41E-04
Bleaching earth	kg	9.15E-03	34.54	3.16E-01
Phosphoric acid (H ₃ PO ₄)	kg	5.08E-04	32.62	1.86E-02
Labor	MJ	2.30E-03	–	2.30E-03
Electricity	MJ	3.41E-01	–	3.41E-01
Transportation (petroleum diesel)				
<i>Chemicals to oil refinery</i>	kg	6.86E-04	48.10	3.29E-02
<i>RBDPO/RBDPKO to biodiesel unit</i>	kg	2.53E-02	48.10	1.217
<i>Total energy input</i>	<i>MJ</i>			<i>42.565</i>
Palm oil refining outputs				
RBDPO/RBDPKO	kg	1.000	37.60*	37.600
PFAD	kg	0.015	36.01	5.40E-01
Spent bleaching earth	kg	8.25E-03	34.54	2.85E-01
Emissions to air and water				
<i>Steam</i>	kg	4.219	1.36	5.738
<i>NO_x</i>	kg	4.11E-04	296.00	1.22E-01
<i>CO₂</i>	kg	1.65E-01	32.12	5.299
<i>CO</i>	kg	8.56E-02	10.11	8.65E-01
<i>SO₂</i>	kg	1.84E-04	29.50	5.43E-03
<i>Particulate matter</i>	kg	1.62E-04	–	–
<i>Total energy output</i>	<i>MJ</i>			<i>50.454</i>

Table A.6 Energy balance (MJ) for the production of 1 kg biodiesel from CPO/CPKO (Pleanjai and Gheewala 2009; Hassan et al. 2011)

	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Biodiesel production inputs				
CPO/CPKO	kg	0.995	39.40*	39.203
Steam	kg	1.823	1.36	2.971
Process Water	kg	1.49E-01	0.0042	6.26E-04
Methanol	kg	2.63E-01	19.70	5.181
Sodium hydroxide (NaOH)	kg	1.03E-02	19.87	2.05E-01
Phosphoric acid (H ₃ PO ₄)	kg	9.58E-04	32.62	3.12E-02
Sulfuric acid (H ₂ SO ₄)	kg	1.06E-02	33.08	3.51E-01
Labor	MJ	2.93E-03	–	2.93E-03
Electricity	MJ	1.49E-03	–	1.49E-03
Transportation (petroleum diesel)				
<i>Chemicals to biodiesel plant</i>	kg	2.35E-02	48.10	1.130
<i>Biodiesel to diesel station</i>	kg	1.93E-02	48.10	9.28E-01

(continued)

Table A.6 (continued)

	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
<i>Total energy input</i>	<i>MJ</i>			<i>50.005</i>
Biodiesel production outputs				
CPO/CPKO biodiesel	kg	1.000	39.84	39.840
Glycerol	kg	1.44E-02	18.05	2.59E-01
Wastewater	kg	1.91E-01	45.93	8.773
Na ₃ PO ₄	kg	1.40E-03	1.421	1.99E-03
Emissions to air and water				
<i>Steam</i>	kg	1.994	1.36	2.712
<i>NO_x</i>	kg	4.82E-04	296.00	1.43E-01
<i>CO₂</i>	kg	1.32E-01	32.12	4.239
<i>CO</i>	kg	6.23E-02	10.11	6.29E-01
<i>SO₂</i>	kg	1.87E-04	29.50	5.52E-03
<i>Particulate matter</i>	kg	2.38E-04	–	–
<i>Total energy output</i>	<i>MJ</i>			<i>56.603</i>

Table A.7 Energy balance (MJ) for the production of 1 kg RBDPO/RBDPKO biodiesel (Balat 2009; Mittelbach and Remschmidt 2006)

	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Biodiesel production inputs				
RBDPO/RBDPKO	kg	0.999	37.60*	37.562
Steam	kg	1.671	1.36	2.273
Process water	kg	1.45E-01	0.0042	6.09E-04
Methanol	kg	1.23E-01	19.70	2.423
Sodium hydroxide (NaOH)	kg	1.03E-02	19.87	2.05E-01
Phosphoric acid (H ₃ PO ₄)	kg	9.59E-04	32.62	3.13E-02
Labour	MJ	2.93E-03	–	2.93E-03
Electricity	MJ	8.66E-04	–	8.66E-04
Transportation (petroleum diesel)				
<i>Chemicals to biodiesel plant</i>	kg	2.35E-02	48.10	1.130
<i>Biodiesel to diesel station</i>	kg	1.93E-02	48.10	9.28E-01
<i>Total energy input</i>	<i>MJ</i>			<i>44.557</i>
Biodiesel production outputs				
RBDPO/RBDPKO biodiesel (>98 wt%)	kg	1.000	39.84	39.840
Glycerol	kg	9.61E-02	18.05	1.735
Wastewater	kg	5.79E-02	45.93	2.659
Na ₃ PO ₄	kg	1.58E-03	1.421	2.25E-03
Emissions to air and water				
<i>Steam</i>	kg	1.731	1.36	2.822
<i>NO_x</i>	kg	4.86E-04	296.00	1.44E-01
<i>CO₂</i>	kg	1.72E-01	32.12	5.525

(continued)

Table A.7 (continued)

	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
<i>CO</i>	kg	6.29E-02	10.11	6.36E-01
<i>SO₂</i>	kg	1.84E-04	29.50	5.43E-03
<i>Particulate matter</i>	kg	2.33E-04	–	–
<i>Total energy output</i>	<i>MJ</i>			53.369

Table A.8 Energy balance (MJ) for the production of 1 kg PFAD biodiesel (Chongkhong et al. 2007)

	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Biodiesel production inputs				
PFAD	kg	0.874	36.01	31.473
Steam	kg	1.621	1.36	2.205
Process water	kg	1.31E-01	0.0042	5.50E-04
Methanol	kg	4.62E-01	19.70	9.101
Sodium hydroxide (NaOH)	kg	1.17E-02	19.87	2.32E-01
Phosphoric acid (H ₃ PO ₄)	kg	8.42E-04	32.62	2.75E-02
Sulfuric acid (H ₂ SO ₄)	kg	9.31E-03	33.08	3.08E-01
Labor	MJ	2.58E-03	–	2.58E-03
Electricity	MJ	1.31E-03	–	1.31E-03
Transportation (petroleum diesel)				
<i>Chemicals to biodiesel plant</i>	kg	6.86E-04	48.10	3.29E-02
<i>Biodiesel to diesel station</i>	kg	2.53E-02	48.10	1.217
<i>Total energy input</i>	<i>MJ</i>			44.601
Biodiesel production outputs				
PFAD biodiesel	kg	1.000	39.84	39.840
Glycerol	kg	1.26E-02	18.05	2.23E-01
Wastewater	kg	1.68E-01	45.93	7.716
Na ₃ PO ₄	kg	1.24E-03	1.421	1.76E-03
Emissions to air and water				
<i>Steam</i>	kg	1.753	1.36	2.384
<i>NO_x</i>	kg	4.51E-04	296.00	1.33E-01
<i>CO₂</i>	kg	1.19E-01	32.12	3.822
<i>CO</i>	kg	5.49E-02	10.11	5.56E-01
<i>SO₂</i>	kg	1.75E-04	29.50	5.16E-03
<i>Particulate matter</i>	kg	2.19E-04	–	–
<i>Total energy output</i>	<i>MJ</i>			54.681

Table A.9 Energy balance (MJ) for biodiesel use in diesel engines (Gabi 4 database)

	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Biodiesel production inputs				
Palm biodiesel*	kg	1.000	39.84	39.84
<i>Total energy input</i>	<i>MJ</i>			<i>39.84</i>
Biodiesel production outputs				
Emissions to air				
<i>NO_x</i>	kg	1.35E−02	296.00	3.996
<i>CO₂</i>	kg	−1.87E+01	32.12	−600.644
<i>CO</i>	kg	−5.11E−02	10.11	−5.17E−01
<i>SO₂</i>	kg	−4.21E−03	29.50	−1.24E−01
<i>Hydrocarbons</i>	kg	−4.55E−02	−	−
<i>Particulate matter</i>		−4.16E−02	−	−
<i>Total energy output</i>	<i>MJ</i>			<i>−597.289</i>

Appendix B

Table. B.1

Table B.1 Energy balance (MJ) for the production of 1.0 MJ bioelectricity from solid palm biomass (Liu and Gibbs 2003; Camargo 1990)

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
CHP plant inputs				
PPF	kg	1.437	19.22	27.619
PKS	kg	0.366	22.14	8.103
Bio-electricity	MJ	3.12E-01	–	3.12E-01
Diesel to start-up boiler	kg	1.73E-03	48.10	8.34E-02
Water consumption by boiler	kg	7.044	0.0042	2.96E-02
Labor	MJ	1.92E-02	–	1.92E-02
<i>Total energy input</i>	<i>MJ</i>			<i>36.165</i>
CHP plant outputs				
Process steam	kg	7.001	1.36	9.521
Heat	MJ	13.21	–	13.208
Bio-electricity	MJ	1.00	–	1.00
Boiler ash	kg	2.82E-02	6.650	1.88E-01
Emissions to air (flue gas from stack)				
<i>Steam</i>	kg	4.30E-02	1.36	5.85E-02
<i>NO_x</i>	kg	3.38E-03	296.00	1.000
<i>CO₂</i>	kg	2.194	32.12	70.470
<i>CO</i>	kg	1.69E-01	10.11	1.709
<i>SO₂</i>	kg	2.82E-03	29.50	8.32E-02
<i>Particulate matter</i>	kg	3.09E-01	–	–
<i>Total organic carbon (TOC)</i>	kg	1.11E-05	–	–
<i>Volatile organic compounds (VOC)</i>	kg	4.21E-06	–	–
<i>Total energy output</i>	<i>MJ</i>			<i>97.238</i>

Appendix C

Table. C.1, Table. C.2, Table. C.3, Table. C.4

Table C.1 Energy balance (MJ) for the production of 1 kg palm bioethanol(Spatariet al. 2005, 2010)

	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Bioethanol production inputs				
OPF	kg	2.923	20.51	59.951
Steam	kg	8.238	1.36	11.204
Process water	kg	158.428	0.0042	6.65E-01
Sulfuric acid (H ₂ SO ₄)	kg	1.19E-01	33.08	3.937
Yeast	kg	1.22E-02	11.40	1.39E-01
Lime	kg	4.56E-02	7.98	3.64E-01
Labor	MJ	3.98E-03	–	3.98E-03
Electricity and steam	MJ	7.313	–	7.313
Transportation (petroleum diesel)				
<i>Chemicals to bioethanol plant</i>	kg	9.12E-04	48.10	4.39E-02
<i>Bioethanol to pumping station</i>	kg	4.02E-05	48.10	1.93E-03
<i>Total energy input</i>	<i>MJ</i>			83.623
Bioethanol production outputs				
OPF bioethanol	kg	1.000	26.79	26.79
Lignin	kg	0.569	18.05	10.27
Wastewater	kg	143.458	16.22	2326.89
Emissions to air and water				
<i>Steam</i>	kg	7.351	1.36	9.997
<i>NO_x</i>	kg	1.65E-03	296.00	4.88E-01
<i>CO₂</i>	kg	4.36E-01	32.12	14.00
<i>CO</i>	kg	2.01E-01	10.11	2.032
<i>SO₂</i>	kg	6.41E-04	29.50	1.89E-02
<i>Particulate matter</i>	kg	8.02E-04	–	–
<i>Total energy output</i>	<i>MJ</i>			2390.486

Table C.2 Energy balance (MJ) for bioethanol use in gasoline engines (Gabi four database)

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Bioethanol production inputs				
Palm bioethanol	kg	1.000	39.84	39.84
<i>Total energy input</i>	<i>MJ</i>			39.84
Bioethanol production outputs				
Emissions to air				
<i>NO_x</i>	kg	1.91E−02	296.00	5.654
<i>CO₂</i>	kg	−2.77E+01	32.12	−889.724
<i>CO</i>	kg	−7.33E−02	10.11	−7.41E−01
<i>SO₂</i>	kg	−5.03E−03	29.50	−1.48E−01
<i>Hydrocarbons</i>	kg	−6.14E−02	−	−
<i>Particulate matter</i>		−5.31E−02	−	−
<i>Total energy output</i>	<i>MJ</i>			−884.959

Table C.3 Energy balance (MJ) for the production of 1 kg palm bio-methanol from palm bio-syngas (Renó et al. 2011; Nakagawa and Harada 2004)

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Bio-methanol production inputs				
EFB	kg	2.000	20.47	40.940
Steam	kg	5.291	1.36	7.196
Process water	kg	36.671	0.0042	1.54E−01
Labor	MJ	2.72E−03	−	2.72E−03
Zinc catalyst methanol synthesis	kg	0.731	1.59	1.162
Oxygen	kg	5.52E−01	8.24	4.55
Electricity	MJ	5.879	−	5.879
Transportation (petroleum diesel)				
<i>Bio-methanol to pumping station</i>	kg	4.02E−05	48.10	1.93E−03
<i>Total energy input</i>	<i>MJ</i>			59.886
Bio-methanol production outputs				
EFB bio-methanol	kg	1.000	22.60	22.600
Bio-syngas	kg	4.200	7.96	33.432
Fly ash	kg	3.13E−02	16.22	5.07E−01
Tar	kg	1.55E−02	30.00	4.65E−04
Emissions to air, water, and soil				
<i>Steam</i>	kg	1.821	1.36	2.477
<i>NO_x</i>	kg	5.89E−02	296.00	17.434
<i>CO₂</i>	kg	1.830	32.12	58.779
<i>CO</i>	kg	1.12E−03	10.11	1.13E−02
<i>SO₂</i>	kg	5.24E−04	29.50	1.55E−02
<i>CH₄</i>	kg	2.34E−04	7.96	1.86E−03
<i>Residual gas</i>	kg	9.17E−02	7.96	7.29E−01
<i>Particulate matter</i>	kg	5.11E−03	−	−

(continued)

Table C.3 (continued)

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
<i>Volatile organic compounds (VOC)</i>	kg	8.97E-05	–	–
<i>Total organic carbon (TOC)</i>	kg	4.00	–	–
<i>Alkalis</i>	kg	6.50E-04	–	–
<i>Total energy output</i>	<i>MJ</i>			<i>135.987</i>

Table C.4 Energy balance (MJ) for bio-methanol use in gasoline engines

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
Bio-methanol production inputs				
Palm bio-methanol	kg	1.000	39.84	39.84
<i>Total energy input</i>	<i>MJ</i>			<i>39.84</i>
Bio-methanol production outputs				
Emissions to air				
<i>NO_x</i>	kg	1.73E-02	296.00	5.121
<i>CO₂</i>	kg	–2.01E+01	32.12	–645.612
<i>CO</i>	kg	–5.62E-02	10.11	–5.68E-01
<i>SO₂</i>	kg	–4.76E-03	29.50	–1.40E-01
<i>Hydrocarbons</i>	kg	–5.01E-02	–	–
<i>Particulate matter</i>		–4.92E-02	–	–
<i>Total energy output</i>	<i>MJ</i>			<i>–641.199</i>

Appendix D

Table. D.1

Table D.1 Energy balance (MJ) for the production of 1 MJ biogas from POME for bio-electricity

Inventory	Unit	Quantity	Energy coefficient (MJ/kg)	Total energy (MJ)
System's inputs				
POME	kg	2.678	21.41	57.336
Electricity	MJ	1.87E-01	—	1.87E-01
Activated carbon for H ₂ S removal	kg	0.5700	32.60	18.580
Labor	MJ	3.84E-03	—	3.84E-03
<i>Total energy input</i>	<i>MJ</i>			<i>76.107</i>
System's outputs				
Biogas	MJ	1.000	—	1.000
Heat	MJ	3.85E-01	—	3.85E-01
Steam	kg	3.25E-01	1.36	4.42E-01
Bio-electricity	MJ	3.06E-01	—	3.06E-01
Slurry	kg	2.593	18.65	48.359
Emissions to air and water				
<i>NO_x</i>	kg	1.38E-03	296.00	4.08E-01
<i>H₂S</i>	kg	1.11E-03	15.22	1.69E-02
<i>CH₄</i>	kg	2.03E-03	7.96	1.62E-02
<i>CO₂</i>	kg	1.72E-03	32.12	5.52E-02
<i>CO</i>	kg	6.41E-02	10.11	6.48E-01
<i>SO₂</i>	kg	8.77E-02	29.50	2.587
<i>Particulate matter</i>	kg	1.73E-03	—	—
<i>Volatile organic compounds (VOC)</i>	kg	2.92E-04	—	—
<i>Total energy output</i>	<i>MJ</i>			<i>54.223</i>

Note: Net energy ratio (NER) = net entry output/net entry input; net energy value (NEV) = energy content of biodiesel (and its co-products)—net energy input

Appendix E

Table. E.1, Table. E.2

Table E.1 Key issues of dimensions of sustainability

Sustainability key Issues	Economic dimensions	Environmental dimensions	Social dimensions
Stocks	– Maintenance of resource balance in ensuring the availability of enough capital stocks, employment, social cohesion, cultural capital, etc.		
Efficiency	– Ensuring the availability of supplies of resources – Optimum utilization of the factors of production like labor for high productivity – Viability of rural areas – Competitive productions within the community	– Minimization of emissions and wastes into the environment – Efficient use of resources – Utilization of wastes for value added bio-products	– Creation and maintenance of employment – Institutional efficiencies (regulatory framework, informal relationships, and steering mechanisms)
Equity	– Contribution to rural development and viability – Maintaining balanced pattern of development – Maintaining lively and active rural communities	– Setting standards for pollution control – Remuneration of environmental services	– Equal and fair standard of living for rural communities – Equal opportunities for men and women in rural communities – Conducive labor conditions – Protection of culture and livelihoods of communities – Ethical production methods and welfare of living organisms around the communities

Modified from OECD (2001)

Table E.2 Examples of sustainability indicators

Economic indicators	Environmental indicators	Socio-economic and cultural indicators	Socio-territorial indicators
– Viability – Financial autonomy – Specialization – Dependency on direct payment – Invested capital – Efficiency – Income parity – Employment – Assets and liabilities	– Direct energy utilization – Indirect energy inputs – Type and area of resource production	– Share of labor force in resource development and production – Population and share in total population – Pensioners and share in total population – Unemployment rate – Quality of housing – Cooperations among workers – Behavior of workers	– Quality of buildings and landscape – Access to land – Product quality – Social structures – Social services – Joint use of resources – Contribution to employment – Training – Impacts on livelihood – Sense of isolation – Imported resources from neighboring countries

Modified from OECD (2001)

Appendix F

Environmental Impacts Associated with Palm Biofuels Production

Land Use Change

For the past 30–50 years, oil palm plantation in Malaysia and Indonesia, for instance, has been established and developed on lands which were once used to cultivate rubber, cocoa, and coconut. The rate of clearing of new forest lands for oil palm plantations has decreased tremendously over the past three decades due to the evolution of responsible or sustainable agriculture for environmental protection. The contributions made by Malaysia (the world's second largest producer and leading exporter of palm oil) to the world's oils and fats growth come from only about 1.84 % of the world's total land area (231 million ha) that is under vegetable oil cultivation (OECD-FAO 2011). These statistics are incomparable to the situations found in the USA and Europe whose biofuels feedstocks are mainly from rapeseeds, soybeans, corn, sorghum, etc., that need large land areas for the production of small amounts of vegetable oil. Land availability for oil palm plantation is not a major problem for the industry as there are vast areas of *alang-alang* grassland and degraded lands readily available in Malaysia (about 0.1–0.5 million ha representing about 0.3–1.5 % of total area) and Indonesia (about 7.5–13.0 ha representing about 407 % of total area) for oil palm expansion (Corley and Tinker 2003; Chin 2009). This kind of land-use change is found to save GHG emissions resulting from oil palm cultivation. Indonesia became the third largest contributor to GHG emissions in 2005 due to land-use change (conversion of forests and peat lands for plantations) for agriculture crops of which oil palm cultivation took a greater share but due to the adoption of sustainable management practices, the emissions have reduced. Figure F.1 shows the GHG emissions from different land-use changes for oil palm production over 25 economic years of the oil palm.

The ability of soils to accumulate carbon depends on the type of land used and the methods of agricultural practices and management (Lal 2003). For instance, organic soils have high carbon stocks (about 41,550 Pg C) compared to vegetation land (about 500–650 Pg C) (Lal 2003). Normally, direct land use (e.g. ploughing of uncultivated land for oil palm production) may cause the removal of substantial amount of carbon from the soil in the form of carbon dioxide that contribute to

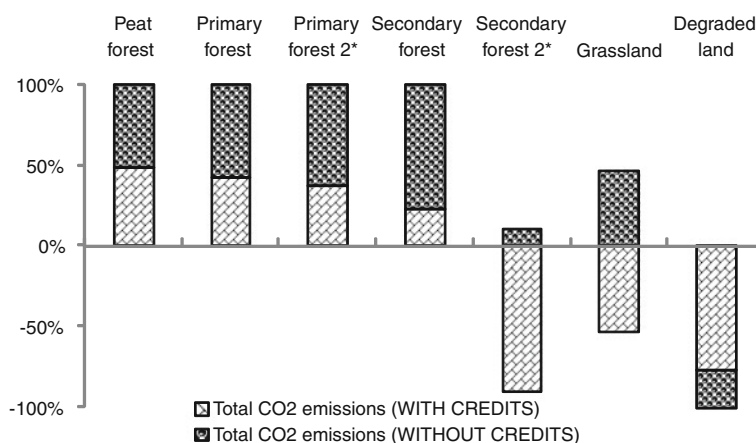


Fig. F.1 GHG emissions from oil palm cultivation processes using different land types. * refers to land type with replacement

GHG emissions (Wicke et al. 2008; Stephenson et al. 2010). On the other hand, if indirect land-use change (e.g. using previously used and idle arable land for oil palm cultivation) is involved, significant improvement in GHG emissions contributions to environmental degradation would be recorded. Carbon losses due to land-use change (either direct or indirect) are serious environmental concerns (Searchinger 2008) but are rarely incorporated into LCA studies of biofuels production.

The oil palm is a perennial crop which when cultivated on land that is either arable or marginal can sequester carbon from the atmosphere though this phenomenon depends on other factors. Biofuels that are produced from oil palm biomass would record GHG savings from this carbon sequestration, which would improve the environmental performance of the system and products. Depending on the land's initial carbon content, agricultural practices, the amount of organic carbon added to the soil during oil palm cultivation as well as the rate of soil carbon pools decomposition, the sequestration of carbon from oil palm cultivation might differ (Grogan and Matthews 2001).

Climate Change

Climate change is the significant irreversible change in the average statistical distribution of the weather or atmospheric patterns over a period. This is the impact related to emissions from human activities resulting in high doses of GHG (apart from the natural GHG) contributing to global warming and other environmental problems. The greenhouse effect is the process by which absorption and emission of infrared radiation by gases in the atmosphere warm

a planet's lower atmosphere and surface. The major contributing factor is the human-induced alterations to the ecosystem like clearing of bushes using fossil fuel use, etc., which result in global warming. Global warming is the rise in the earth's atmospheric and oceans' average temperatures because of these human activities. Generally, GHG emissions related to palm biofuel production include:

- Land and forest clearing using machines that consume fossil fuel.
- Emissions related to the use of fertilizers and pesticides during cultivation. During fertilizer application, about 40–60 % of the N is left in the soil which leads to emission of N_2O . For instance, about 1 % N_2O –N of total N applied to the soil is emitted after fertilizer application. N_2O emissions is about 616 kg CO_2 -eq./ha/year (Nikander 2008). The global warming potential of N_2O is about 296 more potent than CO_2 (IPCC 2006). Mulch and organic fertilizers are found to contribute to GHG emissions reduction and help improve carbon sequestration in the soil and soil organic matter (Searchinger 2008; Nikander 2008; ERIA 2007).
- Variations in solar radiations received by the oil palm plantation
- Emissions related to the use of fossil fuels during palm oil and palm biofuels production. In a small capacity palm oil mill which processes about 100 tons of FFB/day, about 108,000 tons of CO_2 is emitted (especially from wastewater) which is equivalent to burning about 40 million liters fossil fuel for 3 years (Searchinger 2008).
- CH_4 , N_2O and CO_2 emissions from POME in open ponds. GHG emissions from POME is about 2,500–3,800 kg CO_2 -eq/ha/year (Nikander 2008) or 5.5 kg CH_4 /ton POME (Yacob et al. 2006).
- Emissions resulting from changes in carbon stocks during oil palm cultivation practices. GHG emissions from peat degradation or conversion of peat lands to oil palm plantation are in the range of 1.8 to 7.3 kg $\text{CO}_2/\text{m}^2/\text{year}$ (Germer and Sauerborn 2008; Wicke et al. 2008; Reijnders and Huijbregts 2008). At about 80 cm drainage depth of peat land, about 54 tons CO_2 eq./ha/year is emitted during peat clearing for oil palm cultivation (RFA 2008). On the contrary, oil palm plantations are found to assimilate at least 36.5 tons of dry matter/ha/year better than natural forest (25.7 tons) (Henson 1999). Oil palm plantations on peat lands are able to reduce global warming potential to about 5706 g $\text{CO}_2/\text{m}^2/\text{year}$ compared to peat swamp forests (Wicke et al. 2008).

On the other hand, oil palm like all other plants, absorb CO_2 and emit O_2 into the atmosphere through photosynthesis. For instance in 2006, oil palm cultivation contributed about 21.3 tons/ha O_2 into the atmospheric oxygen while soybean cultivation contributed about 2.56 tons/ha O_2 (Department of Statistics 2007).

There are other GHG emissions reduction mechanisms that are set under the Kyoto Protocol like the Clean Development Mechanism (CDM) which supports industries by encouraging them with carbon credit earnings. In most palm oil producing countries like Malaysia, Indonesia, Colombia, etc., CDM projects are being implemented by the oil palm industries (though only a few palm oil companies are involved) mainly through CH_4 capture from POME for sustainable

environment (Becerra and Hoof 2005; Hanim 2010). In Malaysia, for instance, there are about 56 CDM projects being implemented by about 60 palm oil mills for the conversion of oil palm wastes into bioenergy (Hanim 2010). Another GHG emissions reduction mechanism is the Reducing Emissions from Deforestation and Degradation (REDD+)¹ whose main aim is to give financial supports in the form of subsidies and compensations to industries and countries able to reduce GHG emissions by a set level (Scholz and Schmidt 2008). Though these mechanisms may help in the short term, industries must be encouraged to stop polluting the environment rather than giving them profits for polluting little. Concerning palm oil industries, Butler et al. (2008) carried out a comparative profitability assessment for a system which converts forests into oil palm plantations and another conserving the forest to earn credits. Their conclusion was that, a system which converts forests into oil palm plantations is more profitable than that which earns credits for conserving it. If the REDD schemes were to accept credits from forest conservation, it would have been profitable to conserve forests to earn carbon credits.

Another strategy to reduce climate change impacts include the holistic market-based approaches like the World Resources Institute (WRI) Palm oil, Timber, Carbon Offset (POTICO), International Finance Corporation (IFC) Biodiversity and Agricultural Commodities Program (BACP) which involve different players in the supply chain. The BACP provides grants for oil palm projects that promotes biodiversity conservation and implements the best management practices (BMP).

If sustainable or responsible management practices are enforced during palm biofuel production, the industry would contribute positively toward global carbon-neutrality, hence achieving sustainable environmental growth in terms of climate change.

Deforestation and Loss of Biodiversity

Due to oil palm cultivation, until 2010, Indonesia recorded forest cover depletion of 44.4 % since 1985 and this value is projected to decrease to about 32.6 % (Rautner et al. 2005) due to the implementation of sustainable principles and criteria by the oil palm industries. In Malaysia, from 1985 to 2002, over 14 million hectares of forests had depleted due to land clearing for oil palm agriculture (MPOB 2011). However, the trend keeps decreasing due to the implementation of responsible production practices outlined by the RSPO. The impacts of deforestation on the environment include loss of biodiversity, climate change, and hydrological changes resulting in unsatisfactory rainfall patterns globally. Due to these impacts of deforestation, the population of humans and animals decreases as the humans resettle at different areas whilst the animals (like Asian elephant,

¹ The (+) attached to REDD represents the addition of conservation and enhancement of carbon stocks through mechanisms like sequestration, etc.

orangutan, Sumatran tiger, etc.) get extinct from the forests to other habitats resulting in habitat fragmentation. During deforestation, the extinction of pollinators that participate in sexual reproduction of the oil palm for cross-pollination is observed. As habitat fragmentation keep increasing, there evolve increased conflicts between these living organisms that fall victim to the impacts from deforestation. In Malaysia for instance, there was a reported incidence of human–elephant conflicts along the floodplains of one river due to the fragmentation of the natural habitat of the elephants for oil palm plantation (Teoh and Tan 2007). Other animals like the Bornean orangutan and Sumatran orangutan have been listed by the World Conservation Union (WCU) as critically endangered species in Asia (Nellemann et al. 2007). Land-use change from forest lands to degraded lands can reduce these losses to biodiversity (see Appendix F.1).

Acidification and Eutrophication

During the production of palm biofuels, acid compounds from fertilizers, herbicides, biofuels production, raw materials, and chemicals are usually converted into acids which are emitted into the atmosphere and deposited in water bodies and soils which eventually decrease the pH and increase the acidity (Pleanjai et al. 2004). This phenomenon is termed acidification. Examples of compounds or substances that contribute to acidification are CO_2 , SO_2 , NO_x , etc. The introduction of some types of fertilizers like ammonium fertilizers into the oil palm industry for agriculture has continually aided in increasing soil acidification. Soraya et al. (2012) reported that, during the production chain of palm biodiesel, the plantation stage contributed the highest emissions (about 34 %) that resulted in acidification (see also Chap. 5). During the conversion of the palm feedstock into palm biofuels, chemicals like sulfuric acid, sodium hydroxide, etc., are utilized in substantial amounts. In the mill, refinery, and palm biofuel production plants, water is used in large quantities and the compositions of the wastewater include acidifying causing agents. Smallholders of palm oil production do not normally treat their wastewater, which is highly acidic. Most of the biofuels production plants also do not treat their wastes before discharge. These chemicals are potential sources of emissions that cause acidification and eutrophication. The major effects of acidification and eutrophication include loss of living organisms in freshwater bodies, seas, and oceans as well as fauna and flora in the soils.

Again, the use of fossil fuels during palm biofuels production also results in acidification and eutrophication. Apart from the few palm oil mills that generate bioelectricity for their processing activities, all the other stages of the palm biofuel production involve heavy use of fossil diesel which are major causes of acidification and eutrophication. The combustion of fossil fuels release sulfuric, carbonic, and nitric acids which fall onto the earth as acid rain affecting living organisms. During land clearing for oil palm plantations and plant constructions

for biofuels production, most of the machines employed utilize fossil fuel which release significant amounts of acidifying causing agents into the environment resulting in acidification and eutrophication.

Ecotoxicity and Human Health

Ecotoxicity defines the state or fate of the ecosystem when affected by toxic substances for an infinite time horizon and it can be measured in Potentially Disappeared Fraction of species (PDF $\text{m}^2 \text{yr}$). The use of chemicals and fossil fuels during palm biofuels production results in emissions of dangerous substances into the environment (air, water, soil, etc.) which pose many health risks for workers and nearby inhabitants. Women working in palm plantations are mostly assigned to herbicide and pesticide applications. The exposure of these workers to dangerous chemicals result in health hazards like respiratory diseases.

The combustion of palm biofuels also release significant amount of dangerous gases like NO_x , CO, VOC, SO_x , formaldehydes, acetaldehydes, acrolein, methanol, etc., which are toxic to the atmospheric air, hence dangerous to human health. In palm oil mills, steam and bioelectricity are generated from oil palm biomass which also release dangerous emissions that cause risks to human health.

Again, drainages (caused by erosions etc.) from oil palm plantations contain hazardous chemicals which when they enter water bodies, may release toxins into them to cause the death of aquatic organisms. [Chapter 4](#) elaborates on sustainable palm biofuels production practices.

Appendix G

Holistic Approaches to Improving the Sustainability of Palm Biofuels Industry

Fig. G.1, G.2, G.3

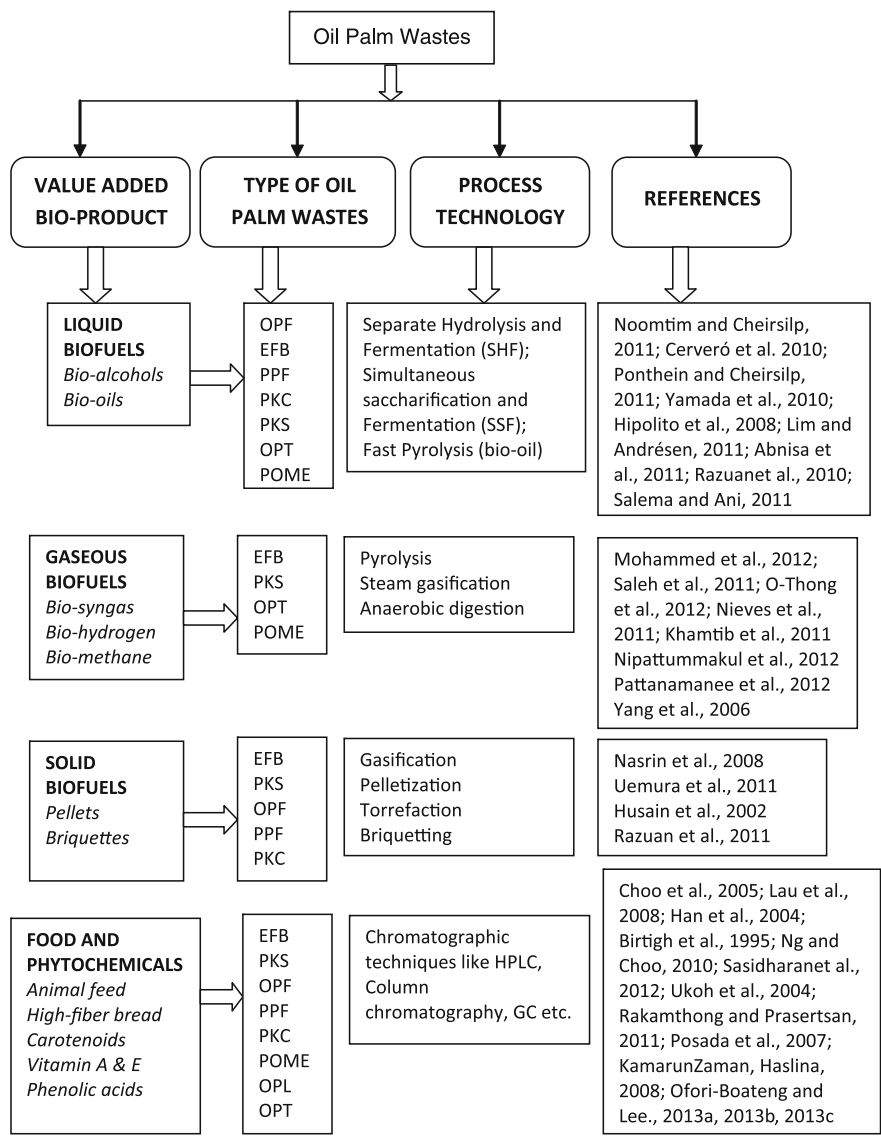


Fig. G.1 Transformation of oil palm plantation wastes into value added bio-products

K. T. Lee and C. Ofori-Boateng, *Sustainability of Biofuel Production*

from *Oil Palm Biomass*, Green Energy and Technology,

DOI: 10.1007/978-981-4451-70-3, © Springer Science+Business Media Singapore 2013

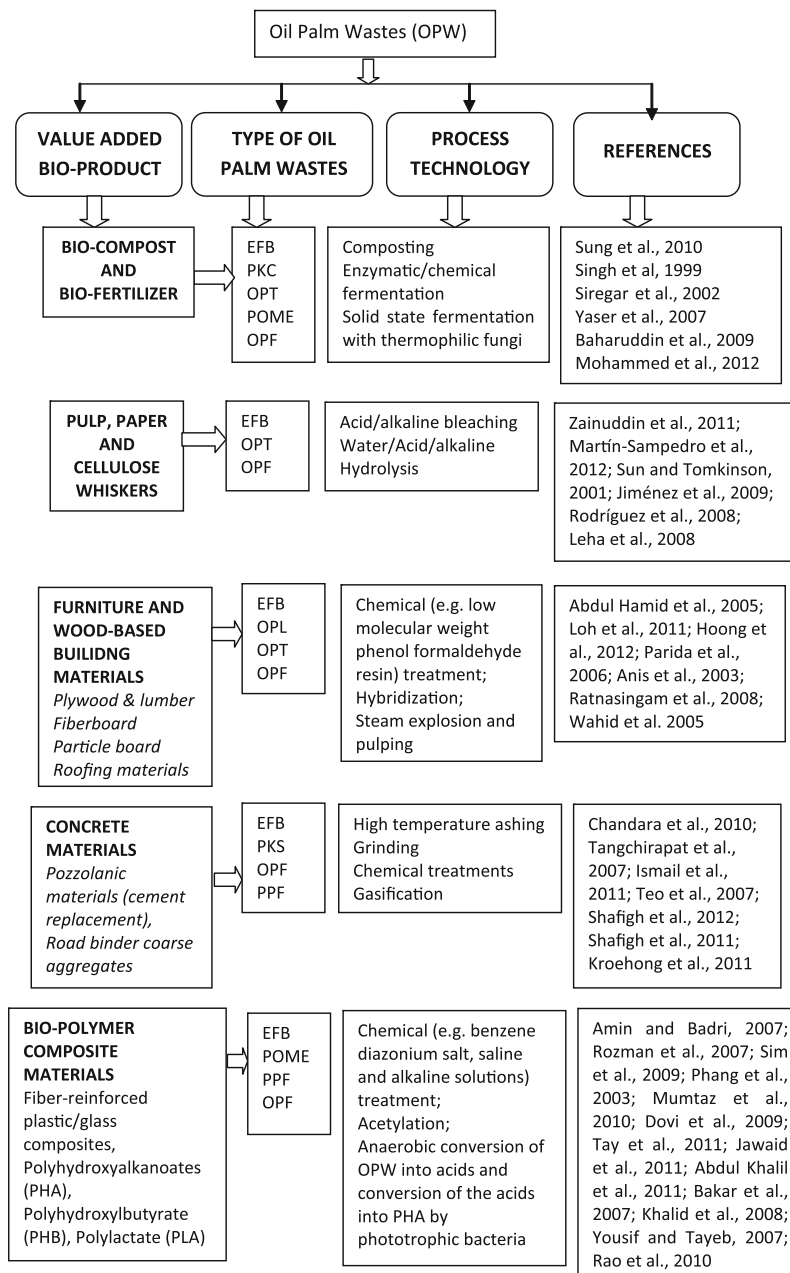


Fig. G.2 Transformation of oil palm plantation wastes into value added bio-products

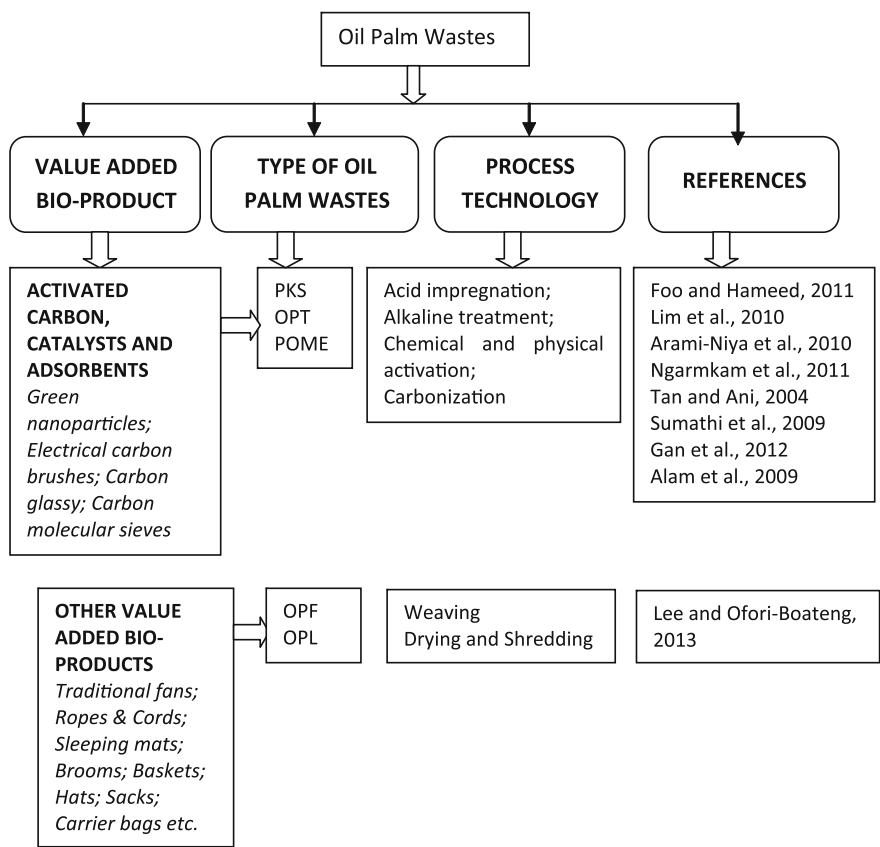


Fig. G.3 Transformation of oil palm plantation wastes into value added bio-products. OPF (Oil palm fronds); OPR (Oil palm roots); OPW (Oil palm wastes); OPT (Oil palm trunks); OPL (Oil palm leaves); PKS (Palm kernel shells); PKC (Palm kernel cake); POME (Palm oil mill effluent); PPF (Palm pressed fiber); EFB (Empty fruit bunches)

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Glossary

Acetogenesis Biological reaction where volatile fatty acids are converted into acetic acid, carbon dioxide, and hydrogen

Acidification Accumulation of hydrogen cations due to proton donor addition which reduces the pH a system or substance

Acidogenesis Biological reaction where simple monomers in an organic substance are converted into volatile fatty acids

Biochemical oxygen demand (BOD) Amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down organic material present in a given water sample at certain temperature over a specific time period

Biofuel Any liquid, solid, or gaseous fuels that are derived from the conversion of biomass or organic matter

Biogas Gaseous form of biofuel produced through anaerobic digestion or gasification of organic materials

Biomass Organic matter which is constantly available on renewable basis and could be in the form of solid or liquid

Biomethane Upgraded biogas, which is cleaned from CO₂ and other gases with about 96 % purity

Carotenoids A large group of isoprenoid structures with different numbers, positions, and configurations of conjugated double bonds

Chemical Oxygen Demand (COD) Amount of oxygen required to degrade the organic compounds of wastewater

Degradation Occurrence where the quality of a resource or product is removed in a consumptive process or system

Elaeis guineensis A common variety of the oil palm which originated from Africa and is the main source of palm oil

Enthalpy A thermodynamic function, which represents the total heat content of a system

Entropy A thermodynamic function, which measures the degree of disorder in a closed but dynamic system

Exergy The maximum useful energy available to perform work in order to bring the system into equilibrium with a heat reservoir

Exergy Loss The part of exergy input which is not changed into useful exergy

Feedstock A major raw material that is fed into a system for conversion into a useful product

Fermentation Metabolic process of converting sugar into carbon dioxide and alcohol with microorganisms like yeast

Free fatty acid Fatty acid in unbound form, which may be removed during processing

Gasification Process of converting solid biomass or fossil-based carbonaceous materials into hydrogen, carbon dioxide, and carbon monoxide using high temperatures and controlled amount of oxygen or steam without combusting the materials

Greenhouse gas Gas in the atmosphere that absorbs and emits infrared radiations

Hydrogenation Chemical reaction occurring between molecular hydrogen and another compound or material like biomass in the presence of catalyst

Hydrolysis Chemical reaction where organic matter or particulates are solubilized whilst large polymers are converted into simpler monomers

Irreversibility The transition from an initial state to a final state cannot be fully undone. Irreversibility means that there is no process which starts from initial state and restores it completely

Life cycle cost Sum of all recurring and non-recurring costs over the full lifetime of a good, service, structure, or system. It includes purchase prices, installation cost, operating costs, maintenance costs, and residual or salvage values at the end of its useful life

Lignocellulose Plant material or biomass that comprises cellulose, hemicellulose, and lignin

Methanogenesis Biological reaction where acetates are converted into methane and carbon dioxide whilst hydrogen is consumed

NEV Difference between the total energy outputs (the energy content of biofuel and its co-products or without its co-products) and total energy inputs (the total fossil energy inputs in the fuel production cycle)

NER is the ratio of total energy outputs to total energy inputs and reflects the energy efficiency of the process

Oil palm Vascular perennial monocotyledonous insect pollinated tropical oilseed plant or tree that produces palm oil

Oil palm biomass Comprises all organic matter be it edible or non-edible, liquid, or solid that is generated by the oil palm industry during plantation, palm oil milling, refining, palm kernel oil milling, etc

Palm oil Red edible vegetable oil obtained from the mesocarp of the oil palm fruit

Parts per million (ppm) Concentration parameter that expresses the amount of substance in a solvent

Phospholipids Lipids containing phosphoric acid or other phosphorus containing acids in appropriate ester form

Phosphatides Class of compounds that are fatty acid esters of glycerol phosphate with a nitrogen base linked to the phosphate group. Commonly called gums

Phytochemical Chemical bioactive compound that occurs naturally in plants that is responsible for the color and organoleptic properties of plants

Pyrolysis Decomposing large molecules into smaller chain compounds by heating at high temperatures and atmospheric pressure anaerobically with or without catalysts

Refining Industrial technology to obtain edible oils from crude oils through processing steps such as degumming, neutralization, bleaching, and deodorization

Salvage value An estimated value of an asset at the end of its useful life

Soapstock By-product consisting of soap, hydrated gums, water, oil, and other impurities that are obtained from the neutralizing step of a chemical refining process

Sustainability The efficient use of goods and services that respond to basic needs as well as improving the lives of people in a society by minimizing the use of natural resources, toxic materials, and emissions from wastes and pollutants over their life cycle so as not to jeopardize the needs of future generations

Sustainable development Development that meets the needs of the present without compromising the ability of future generations to meet their own need

Transesterification Process of exchanging the organic R'' group of an ester with the organic R' group of an alcohol with or without catalyst

Index

A

Acid detergent fiber, 95
Acidification/eutrophication, 175
Africa, 80
Agalitarian approach, 155
Air pollution, 22
Alcohols, 43
Algae, 35
Allocation methods, 154
American society for testing and materials, 38
Anaerobic digestion, 37
Anaerobic digestion of pome, 128
Annual cost benefit, 207
Asia, 115
Aspen hysys, 191
Aspen plus, 191
Aspen plus software, 225
Assets rights, 262
Assumptions limitations, 160
Attributional life cycle assessment, 153
Availability of feedstocks, 78

B

B15, 140
B20, 38
B100, 38
B5 palm biofuels, 269
Best management practices, 27
Better Sugarcane Initiative, 16
Bio-butanol, 51
Biodiesel, 34
Bioelectricity, 127, 182
Bioethanol, 21, 34, 49
Bio-Ethyl-tertiary-butyl-ether, 57
Biofuel certification, 19
Biofuel industry, 10

Biofuels, 10
Biofuels policies, 268
Biofuels production, 108
Biofuels sustainability, 254
Biogas, 34, 58
Biogas production from pome, 180
Bio-gasoline, 57
Bio-hydrogen, 61
Bio-kerosene, 56
Biomass, 32
Bio-methanol, 49
Bio-methanol production, 177
Bio-oil, 56
Bio-propane, 62
Biorefineries, 139
Bio-syngas, 60
Bio-Synthesis gas, 60
Boiler efficiency, 127
Breakeven point, 195
Briquettes, 65
Briquetting plant, 137
BtL, 57
Byproduct credit, 193

C

Capara procera, 38
Capital cost, 191
Carbon credit projects, 115
Carbon monoxide, 22
Carotenes, 133
Carotino sdn bhd, 140
Cellulose, 95
Cellulosic ethanol, 141
Certified sustainable palm oil, 115
Charcoal, 138
Chemical compositions, 93

Chemical exergy, 221
 Chemical refining, 121
 Child labour, 266
 Chlorofluorocarbons, 4
 Clean development mechanism, 150
 Climate change, 298
 Clostridium acetobutylicum, 51
 CO₂, 22
 CO₂-eq., 168
 Co-enzyme, 133
 Cogeneration, 125
 Commercialization, 68
 Compliance costs, 26
 Components of Exergy, 220
 Composting, transesterification, 37
 Concepts of social sustainability, 255
 Conditions of service, 260
 Conflict resolutions, 260
 Consequential life cycle assessment, 153
 Co-product, 183
 Cost-benefit assessment, 203
 Cover crops, 113
 Cradle-to-cradle, 156
 Cradle-to-gate, 156
 Cradle-to-grave, 156
 Criteria, 11
 Crude palm oil, 87
 Culture, 265

D

Data Collection, 159
 Dead state, 219
 Deodorization, 121
 Department of the Environment, 16
 Diesel, 39
 Dimension of sustainability, 6
 Discounted cash flow rate of return, 195
 Diversity losses, 4
 Driving force, 10
 Dura, 81

E

Eco-certification of agriculture, 19
 Eco-efficiency, 152
 Eco invent, 182
 Economic, 5
 Economically sustainable, 189
 Economically viable, 200
 Economic analysis, 190
 Economic feasibility of biodiesel, 198

Economic Impacts, 208
 Economic sustainability, 20
 Ecosystem, 5, 8, 149
 Ecosystem quality, 155
 Ecotoxicity, 22, 171
 Efficiency, 113
 Efficient methods, 129
 Electricity, 141
 Energy, 31
 Energy balance, 161
 Energy efficiency, 139
 Engines, 37
 Entropy, 219
 Entropy generation, 222
 Environment, 7
 Environmental concentrations, 221
 Environmental degradation, 4
 Environmental impact assessment, 151
 Environmental quality act, 16
 Environmental sustainability, 20
 Enzymatic degumming, 123
 Enzymatic method of refining, 122
 Equitable, 260
 Equitable distribution, 190
 European standard on biodiesel, 131
 Exergetic efficiency, 222
 Exergetic life cycle assessment, 218
 Exergoeconomic analysis, 12, 218
 Exergy, 218
 Exergy analysis, 12, 218
 Exergy balance, 228
 Exergy destruction, 221
 Exergy losses, 218

F

Feedstock cost, 190
 Feedstock production, 139
 Feedstocks, 49
 Fermentation, 37
 Fertilizers, 113
 Firewood, 34
 First generation biofuels, 34
 Fixed costs, 195
 Food Security, 267
 For sustainable bioenergy production, 127
 Fossil fuels, 10, 31
 Fourth generation biofuels, 35
 Free fatty acids, 39
 Fresh fruit, 86
 Functional unit, 154
 Future cash flow, 192

G

Gabi 4, 155
Gasoline, 51
Gate-to-gate, 156
General Improvement Options, 245
Global Bioenergy Partnership, 14
Global warming, 299
Governmental agencies, 254
Greenhouse gas, 14
Green technologies, 26
Gross domestic product, 12
Guineensis, 81

H

Habitat fragmentation, 23
Hamilton wentworth regional council, 6
Heat integration, 134
Heat transfer, 246
Hemicelluloses, 95
Holocellulose, 95
Human health, 155
hydrogen, 34
Hydrogenation, 40
Hydrolysis, 237
Hydro processing, 37
Hydrothermal upgrading, 37

I

Immobilized enzymes, 200
Impact categories, 166
Improvement options, 208
Incentives, 20, 202
Indicator dimensions, 13
Indicators, 11
Indonesia, 115
Integrated biofuel plants, 131
Interfaith center on corporate responsibility, 6
International labour organization, 258
International organization for standardization, 154
Investment cost, 193
Irreversibilities, 218
Irrigation, 113

J

Jatropha curcas L., 32
Job creation, 260
Johannesburg, 5
Juice, 203

K

kamerunicus, 81
kernel nuts, 86
kernel shells, 86

L

Labour Rights, 266
Land availability, 297
Land Use Change, 297
Life cycle Analysis, 12
Life cycle assessment, 150
Life cycle cost, 191
Lignocellulosic materials, 34
Lignocellulosic wastes, 21
Livelihood, 265

M

Macroalgae, 35
Macrocaria, 81
Maintenance cost, 191
Malaysia, 115
Malaysian Palm Oil Board, 133
Malaysian Palm Oil Wildlife Conservation Fund, 269
Mallholders, 27
Mammalian pests, 114
Market fluctuations, 265
Membrane separation, 181
Mesocarp fiber, 86
Mesocarp oil, 86
Methodological frameworks, 154
Microalgae, 35
Microemulsions, 42
Microorganisms, 203
Minerals, 171
Mono alkyl esters, 44

N

National biofuel policy, 150
Natural resources, 4
Net energy ratio, 161
Net energy value, 161
Net present/future value, 195
Net-zero emission, 160
Neutral detergent fibre, 95
NexBtL process, 46
Non-renewable resource, 149
Nordic Ecolabelling principles, 19
Normalization, 156

Novozymes, 55

Nursery, 83

O

Oil palm, 32, 79

Oil palm agriculture, 116

Oil palm biomass, 77

Oil Palm Biomass Cogeneration, 126

Oil palm briquettes, 109

Oil palm expansion, 297

Oil palm industry, 11, 77

Oil palm plantation, 265

Oil palm planting density, 81

Oil palm seedlings, 83

Oil palm wastes, 78

Oleifera, 81

Operating cost, 191

Organic fertilizers, 21

Oslo, 4

P

Palm biodiesel, 164

Palm Bioethanol Production, 174

Palm biomass cogeneration, 170

Palm empty fruit bunches, 86

Palm Fatty Acid Distillate, 92

Palm feedstocks, 133

Palm fruit, 78

Palm Industries Sdn. Bhd, 261

Palm kernel milling, 164

Palm kernel oil, 78, 88

Palm kernel olein, 89

Palm kernel shells, 34

Palm oil, 40

Palm oil industry, 77

Palm oil mill effluent, 93

Palm Oil Milling, 116

Palm oil mills, 113

Palm Oil Refiners Association of Malaysia, 87

Palm oil yield, 209

Palm olein, 88

Palm stearin, 88

Papua New Guinea, 115

Patum Vegetable Oil Company, 115

Payback period, 195

Payback time, 193

Peat land, 114

Pelleting, 138

Pellets, 65

Performance monitoring, 225

Pesticides, 21

Petroleum diesel, 127

Phenolic compounds, 133

Physical exergy, 220

Physical refining, 119

Physico-chemical properties of palm biodiesel, 131

Phytochemicals, 100

Pisifera, 81

PKS briquettes, 243

Plug-to-wheel, 156

Policy initiatives, 268

Policy making and implementation, 13

Political, 11

Political sustainability, 20

Pollution control, 116

Pretreatment, 118

Primary biofuels, 34

Process improvement, 110

Profitability, 195

Purchase cost, 194

Pyrolysed oil, 34

Pyrolysis., 37

Pyrolysis oil, 56

Q

Quality of lives, 259

R

Rapeseed, 40

Rapeseed oil biodiesel, 199

Rate of return on investment, 195

Real palm belts, 80

Reducing Emissions from Deforestation and Forest Degradation's, 110

Refined, bleached, and deodorized, 87

Refining, 118

Refrigeration, 181

Regulations, 268

Renewability, 162

Renewable energy, 139

Renewable energy directive, 257

Renewable Fuel Standard, 20

Renewable Transport Fuels Obligation, 19

Resources, 228

Resources use, 155

Resource utilization, 4

Respiratory organics, 171

Rio de Janeiro, 4

Roundtable on Responsible Soy, 16

Roundtable on Sustainable Biofuels, 15
Roundtable on Sustainable Palm Oil, 16
RSPO, 27
Rural communities, 260
Rural folks, 263

S
Salvage value, 193
Second generation biofuels, 35
Second laws of thermodynamics, 218
Secondary biofuels, 34
Sensitivity analysis, 205
Separate hydrolysis and fermentation, 234
SimaPro, 155
Simultaneous hydrogenation and catalytic/
thermal cracking, 41
Smallholders, 115
Social, 5
Social biofuel sustainability, 20
Social capital, 9
Social impact assessment, 256
Social stresses, 261
Social sustainability criteria, 256
Social sustainability of␣palm biofuels,
257
Society, 189
Socio-economic benefits, 208
Socio-economic impacts, 190
Socio-political sustainability, 254
Soluble enzyme, 200
Soya bean, 40
Stakeholders, 260
Standard chemical exergy, 224
Steam explosion, 237
Sterols, 133
Subsidies, 202
Sugar, 203
Sustainability framework, 11
Sustainability Initiatives and␣Certifica-
tions of␣Biofuels, 15
Sustainability principles, 11
Sustainability standard, 12
Sustainable agriculture, 19
Sustainable consumption, 4
Sustainable Oil Palm Agriculture, 110
Sustainable palm production, 258
Sustainable practices, 26, 114
Sustainable production, 4
Swan labeling of Fuel, 19
Syngas, biohydrogen, 34
System boundary, 154

T
Techno-economic assessments, 190
Technological barriers, 67
Technologies for␣Sustainable Produc-
tion, 125
Tenera, 81
Thermochemical conversion, 37
Thermodynamic efficiency, 217
Thermodynamic equilibrium, 221
Thermodynamic improvement potential, 247
Thermodynamic sustainability, 14
Thermoeconomic analysis, 218
Thermoeconomic sustainability, 12
Third generation biofuels, 34
Tillage, 22
Total production cost, 195
Trade, 68
Transesterification, 44
Triglyceride, 43

U
Umberto, 155
UN Commission on Sustainable Development,
6
United Nations Framework on Climate
Change, 150
Unsaponifiables, 40

V
Variable cost, 195
Vegetable oil, 37
Vitamins E, 133

W
Wastes, 4
Wastes utilization, 125
Water scrubbing, 181
Weighting, 156
Well-to-station, well-to-tank, tank-to-wheel,
station-to-wheel, 156
Well-to-wheel, 156
Wood pellets, 34
Working capital, 205

X
xylose, 95