Sudha Goel *Editor*

Advances in Solid and Hazardous Waste Management

Springer

Advances in Solid and Hazardous Waste Management

Sudha Goel
Editor

Advances in Solid and Hazardous Waste Management

Springer

Editor
Sudha Goel
Department of Civil Engineering
Indian Institute of Technology
Kharagpur, WB, India

Co-published by Springer International Publishing, Cham, Switzerland, with Capital Publishing Company, New Delhi, India.

Sold and distributed in North, Central and South America by Springer, 233 Spring Street, New York 10013, USA.

In all other countries, except SAARC countries—Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka—sold and distributed by Springer, Tiergartenstr. 15, 69121 Heidelberg, Germany.

In SAARC countries—Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka—printed book sold and distributed by Capital Publishing Company, 7/28, Mahaveer Street, Ansari Road, Daryaganj, New Delhi 110 002, India.

ISBN 978-3-319-57074-7 ISBN 978-3-319-57076-1 (eBook)
DOI 10.1007/978-3-319-57076-1

Jointly published with Capital Publishing Company, New Delhi, India

Library of Congress Control Number: 2017940476

© Capital Publishing Company, New Delhi, India 2017
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The field of solid and hazardous waste management has been growing exponentially since the 1990s in India and several other countries. This growth has been fairly all-inclusive. Commercial, academic, legal, and administrative interests have resulted in increased spending on projects related to this field. Along with more activity, the field has grown in terms of its scope, and today, it includes more topics than were envisioned in the 1990s. Case studies, reviews, and examples pertaining to such topics in solid and hazardous waste management have been compiled for this book.

The circular economy and the economics of solid waste management are two major chapters in this book. The book also includes characterization, treatment, and management of different types of solid waste: municipal, institutional, biomedical, e-waste, plastics, and fly ash. Sampling and statistical methods for characterizing waste are dealt with in another major chapter in this book. The fate and transport of contaminants leaching from fly ash were modeled using software like WiscLEACH, while the potential for groundwater contamination was modeled using DRASTIC, and are included in this book.

Composting is the best method for recycling the biodegradable fraction of municipal solid waste. The book provides an overview of the fundamentals of microbiology that are necessary for designing and operating biological processes like composting. Several chapters include remote sensing and GIS applications in solid waste management and methods for effectively assimilating these data for various environmental applications. Finally, this volume includes environmental regulations pertaining to solid and hazardous waste management that would benefit students, policy makers, and practitioners.

There are many other issues pertaining to this vast and growing area of engineering research, development, and management that remain to be addressed. I leave that to other experts and students in this field.

Kharagpur, WB, India
Sudha Goel

Acknowledgements

The idea of an edited volume on *Advances in Solid and Hazardous Waste Management* began with two short-term courses that were conducted in 2007 and 2010 in IIT Kharagpur, sponsored by All India Council of Technical Education (AICTE) under the Quality Improvement Program (QIP). The editor would like to acknowledge their financial support and the whole-hearted administrative support of the Civil Engineering Department and Department of Geology and Geophysics. Professor Debashish Sengupta of the Department of Geology and Geophysics has been a major motivator and collaborator in both courses and his contributions are gratefully acknowledged here.

Finally, many thanks to staff, students and teachers (past and present), colleagues, friends and family, who have all contributed in small and big ways to this effort.

Contents

Chapter 1
Solid and Hazardous Waste Management: An Introduction

Sudha Goel

1 Introduction

Solid waste management is now acknowledged as one of the major environmental issues of our times. It remains a challenge for developed countries and is an exponentially growing problem for developing countries. The last four decades are marked by several incidents highlighting problems with solid and hazardous waste management across the world.

1. Trans-boundary shipments of hazardous and solid waste have received worldwide attention and media headlines. Infamous examples include *Khian Sea* which started its journey from Philadelphia in 1986 and *Mobro* which started its journey from New York in 1987; two US barges or ships with cargoes of municipal solid waste that went from one country to another looking for a port to dump their wastes. The *Mobro* went all the way to Belize and brought its cargo back to Brooklyn, New York for incineration and landfilling.[1] Many speculate that *Khian Sea* dumped its cargo somewhere in the Indian Ocean in 1988.[2]
2. Most recently, a fire started on 27 January 2016 in India's oldest and largest open dumping site, Deonar in Mumbai, and was visible in satellite images (shown in Fig. 1.1). It continued for several days leading to complaints of air pollution and closure of schools for 2 days. The massive fire was attributed to the buildup of methane gas in the open dump where the waste had reached heights of more than

---

[1] https://en.wikipedia.org/wiki/Mobro_4000

[2] http://www.neatorama.com/2007/08/15/worlds-most-unwanted-garbage-cargo-of-the-khian-sea/

S. Goel (✉)
Civil Engineering Department, Indian Institute of Technology Kharagpur,
Kharagpur 721302, WB, India
e-mail: sudhagiitkgp@gmail.com

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_1

Fig. 1.1 Plume from a massive fire in a solid waste dump in Deonar, Mumbai on 27 Jan 2016 (http://earthobservatory.nasa.gov/)

30 m. Fires in this dumping site have been recurrent making living conditions in the surrounding areas extremely difficult.

3. Many sources have identified poor solid waste management as one of the major contributing factors to the spread of plague in Surat, India in 1994. Incidents like these led to promulgation of the Municipal Solid Waste (Management and Handling) Rules in India in 2000.
4. Several industrial sites all around the world remain unusable or a toxic nuisance for their neighbours due to improper handling and management of hazardous wastes on-site. One of the earliest and most cited examples in the USA includes Love Canal, Niagara Falls, New York, where toxic waste was dumped through the 1920s and got national attention only in 1976–1978. The Superfund program (under the Resources Conservation and Recovery Act, RCRA for ensuring proper disposal of solid and hazardous waste) was initiated in 1980 in the USA and was the government's response for remediating and rehabilitating such contaminated industrial sites.

1.1 What Is Solid Waste?

Waste is defined as any material that is discarded by the possessor or generator due to its lack of value to them. Therefore, solid waste is defined as any waste material that is neither in liquid nor gaseous state. Further, containerized liquid and gaseous

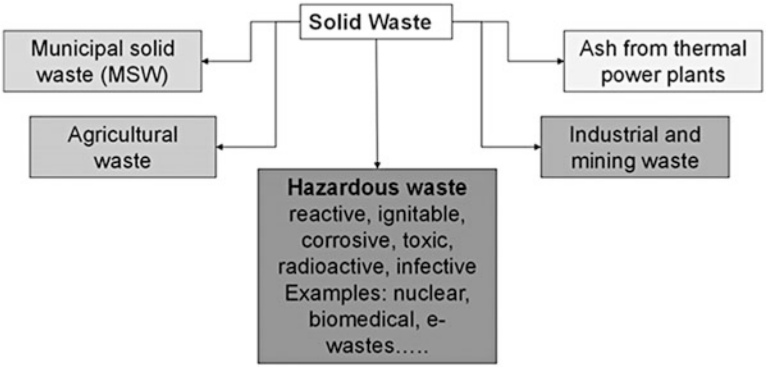


Fig. 1.2 Categories of solid waste

wastes are also included in the term solid waste. Solid waste includes several categories of waste of which the most important ones are shown in Fig. 1.2. and include the following:

(a) *Agricultural and allied industries:* Agrarian economies generate large amounts of agricultural waste during harvest and in food processing activities.
(b) *Industrial and mining waste:* Several countries are heavily dependent on mining of metals and allied industries for their economic growth. Mine tailings constitute a major portion of mining waste.
(c) *Ash from thermal power plants:* Despite the growing share of renewable energy sources, coal-based thermal power generation remains the largest source of electricity world-wide. Burning of coal in thermal power plants generates large quantities of ash. Management and disposal of this ash is a major solid waste management problem today.
(d) *Municipal solid waste:* This category includes waste generated in urban centres and derives from residential, commercial, institutional and municipal activities. It is a relatively small fraction of the total solid waste generated but remains its most visible fraction.
(e) *Hazardous waste:* Hazardous waste is generated in comparatively small amounts compared to the other categories mentioned above. However, it is one of the most important categories of waste due to the severity of its impacts on public health and the environment. Any waste material that is reactive, ignitable, corrosive, toxic, radioactive, or infective is classified as hazardous waste. This category includes radioactive waste, biomedical waste, plastics and electronic waste (e-waste).

A comparison of the different fractions of solid waste generated in India and the USA is shown in Fig. 1.3 and reflects the dominant activities in these countries (Pappu et al. 2007; Masters 1998). Total amount of solid waste generated in India in the late 1990s to 2002 was estimated to be 455 million tons/y (Pappu et al. 2007) while the total waste generated in the USA in 2005 was estimated to be 246 million

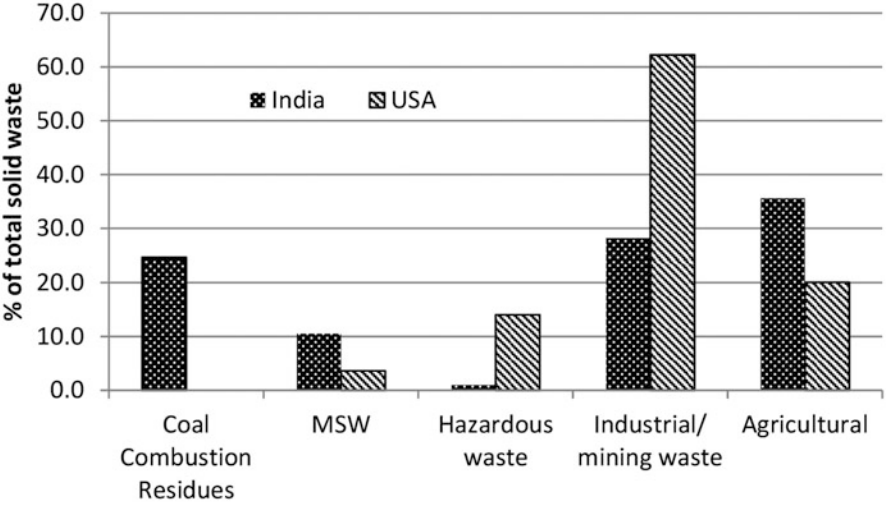


Fig. 1.3 Percent distribution of different fractions of solid waste in India and the USA

tons/y (Masters and Ela 2008). The bulk of solid waste in the USA (more than 60%) originates from industrial and mining activities while agricultural activities are the dominant source of solid wastes in India.

1.2 Importance of Solid Waste Management

Open dumping of municipal solid waste on land is the norm rather than the exception in most low- and middle-income countries (Hoornweg and Bhada-Tata 2012). Despite significant progress in building treatment facilities and landfills in the last couple of decades, open dumping remains the most common disposal option. In India, even after the Municipal Solid Waste (Management and Handling) Rules were promulgated in 2000, most of the total waste collected is dumped on open land. Problems associated with open dumping of solid waste are enormous, long-term as well as short-term, and have far reaching implications as evidenced by the aforementioned incidents.

(a) *Public health hazard:* Open dumps are first and foremost a major hazard to public health. These waste dumps attract pestilent species like flies, rodents, etc. and are breeding grounds for disease vectors like mosquitoes. These open dumps also attract stray animals which often scatter collected waste and contribute to bad traffic conditions and higher accident potential.

(b) *Water pollution:* Open solid waste dumps lead to short-term and long-term contamination of both surface water (SW) and ground water (GW) resources.

These dumps or waste scattered from these dumps act as barriers to natural and engineered drainage channels leading to water-logging in several areas.

(c) *Soil pollution:* Leachate and liquids released from solid waste contain contaminants that are easily sequestered in soil. These contaminants can cause long-term soil toxicity and decreased soil productivity. Further, many of these contaminants can bioaccumulate leading to greater toxicity at higher trophic levels.

(d) *Air pollution:* Contaminants from these open dumps are released into the air due to scattering by wind, and volatilization of contaminants and in extreme cases, there is potential for explosions due to methane buildup in these dumps over the long-term. Another common practice in countries like India is burning of waste in open dumps which leads to the release of extremely toxic contaminants into the air.

(e) *Financial values:* These open waste dumps are an aesthetic nuisance that contribute to loss of civic health and pride, and lower property values in the vicinity leading to serious financial losses for the municipalities and for those owning or using adjacent properties. Examples of the importance of solid waste management become most apparent in low- and middle-income countries when cities wish to host international events like games, festivals and conferences.

2 Integrated Solid Waste Management

Integrated solid waste management takes a holistic approach that should be applied to all functional activities to be undertaken. Specifically, objectives that need to be addressed in integrated solid waste management include:

1. *Minimize public health and environmental impacts* by using appropriate collection, transport, storage and disposal technologies and practices.
2. *Minimize resource consumption:* The concept of a circular economy (detailed in the next chapter) is based on reducing resource consumption thereby reducing the amount of solid waste generated. This also includes implementation of the four Rs: Reduce, Reuse, Recycle and Recover (Goel 2008). Another method for reducing resource consumption is adopting 'Green Design' principles for delivering goods and services (Masters 1998).
3. *Adopt waste-to-energy technologies:* Since energy remains one of the most precious resources in today's world, any technology that allows conversion of waste to useful energy is beneficial.
4. *Minimize greenhouse gas emissions:* Another major issue today is climate change which is driven by the generation of greenhouse gases (GHG) like CO_2 and CH_4. Incineration of waste would result in generation of GHG (Masters and Ela 2008). On the other hand, if organic waste can be converted to end products like biogas or compost, there are net benefits due to reduction in GHG emissions.

Composting and biogas generation are also considered to be carbon-neutral technologies since there is no reliance on fossil fuels.

5. *Minimize use of landfills and conserve land:* Land is another precious resource and it is imperative that land use for landfilling waste be avoided or minimized to the maximum extent possible. Landfilling has several adverse, long-term impacts on public health and the environment and requires long-term post-closure monitoring. Minimizing use of landfills is a better option rather than creating landfills with better or more complex designs.

2.1 Principles

Integrated solid waste management includes several principles that can be incorporated into the design and creation of products and processes and in managing the wastes created during these processes.

2.1.1 Waste Management Hierarchy

The Waste Management Hierarchy defines the order of preference in which to use different waste management options. One of the objectives of Integrated Solid Waste Management is to reduce the amount of waste to be handled. Therefore, the SWM hierarchy shown in Fig. 1.4 has source reduction as the most preferred option followed by waste minimization, reuse, recycling and waste-to-energy conversion. The least preferred options are treatment and disposal options like landfilling which do not result in useful end-products.

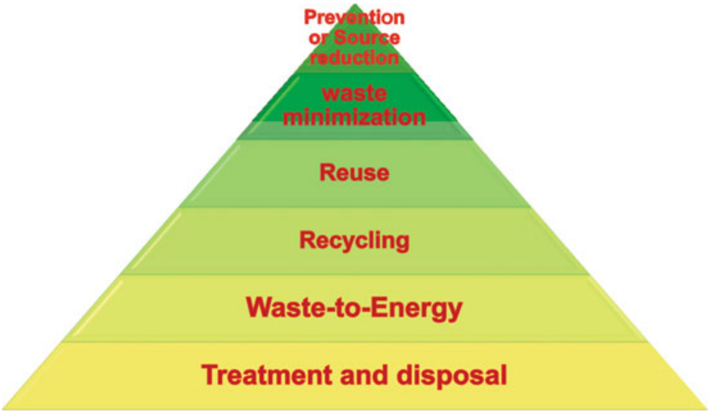


Fig. 1.4 Waste management hierarchy

Source Reduction is based on the concept that 'garbage that is not produced does not have to be collected'. Reduction in resource consumption is the main premise of source reduction and needs to be incorporated into the design of products and processes. Products/processes should be designed to minimize toxicity, weight (packaging) and energy use and should have long service times. Green design includes all of these concepts with the additional objective of minimizing environmental impacts.

Waste Minimization requires that the amount of waste generated be reduced to the maximum extent possible. One example is segregation at source. By separating waste into different fractions at source, the amount of waste to be disposed is reduced or minimized.

Reuse involves using the same product several times, perhaps for different uses. For example, containers and packaging materials like cardboard boxes, etc. are often used multiple times before being discarded.

Recycling involves modifications of the waste products to create newer products. Products made of plastic, paper, glass, metals, etc. are easily recycled at the end of their lives.

Waste-to-Energy is the conversion of waste materials into fuel or energy. The best examples are the use of solid waste for the generation of biogas or biodiesel which serve as fuels or the controlled burning of organic material in incinerators to generate heat and/or electricity.

Treatment and Disposal is the least preferred option in the waste management hierarchy and is resorted to only in the absence of all other possibilities. The best example would be the use of controlled incineration followed by landfilling. If the waste material is low in moisture and organic content making energy conversion difficult, it can be incinerated under controlled conditions. Ash and inert material remaining after incineration can then be landfilled.

2.1.2 The Four Rs

The four Rs of SWM, i.e., Reduce, Reuse, Recycle and Recover are described here with some examples of current practices and some that can be introduced (Goel 2008). Some of these principles are part of the SWM hierarchy.

Reduce The first principle is to reduce the amount of material required to deliver one unit product without sacrificing its utility or quality. Examples include the use of refills in various products like printer cartridges, pens, food packets, other household consumables and use of rechargeable batteries instead of disposable batteries. This principle also includes using materials that have a longer lifetime (reducing the use and need for disposables). Another method of implementing this principle would be to eliminate or reduce the need for certain products. Examples include substituting print media with electronic media and using gas pipelines instead of gas cylinders.

Reuse The monetary incentives in implementing this principle are self-evident. Most people reuse containers of cardboard, plastic, metal and glass for storage and other purposes in homes, offices and business establishments. Packaging materials and furniture are similarly easy to reuse.

Recycle Recycling requires separating different components of waste and reprocessing them into new products. Plastics, paper, steel and aluminum cans, glass bottles and yard waste (composting) are examples of MSW components that can be recycled to create new products. Used furniture or wood is often re-cast into new products.

Recover In general, recyclables should be separated at source. However, often refuse that is collected is unsegregated and desired materials have to be separated (recovered) at a central facility. In India, even though the bulk of recyclable materials are separated at source, it is becoming increasingly evident that some amounts of paper cartons, plastic, foil wrappers, household hazardous items like batteries, tubelights, and thermometers are left in the mixed waste. A materials recovery facility where these materials can be separated from more benign materials like soil and organic matter is essential, especially if the waste is to be composted or biogas generated from it. Developed countries tend to have well-designed materials recovery facilities (MRFs).

2.1.3 Life Cycle Assessment (LCA)

Life cycle assessment also called ‘cradle-to-grave’ assessment is a relatively recent method of accounting for all materials and energy inputs for any product during its entire life. This helps to identify outputs of solid waste, air and water pollutants and waste heat that can be recovered. Materials that are wasted in processing and subsequently, during product reuse and recycling can be recovered and the manufacturing processes can be made more efficient in terms of use of energy, air and water. Final disposal options for any product can be identified during a life-cycle assessment and a comparative analysis of products can be done using this tool to determine the better product in terms of its overall environmental impacts.

2.1.4 Extended Product Life

Products that have a longer service life lead to lower resource consumption and, therefore, lower waste generation. The trend in the last few decades has, however, been towards increasing use of disposables. Ink pens, which used to last for years, were replaced by ballpens with refills that lasted for a few months, and these have now been replaced by ballpens or gelpens that are entirely disposable and cannot be refilled. Many other products are now manufactured with short service lives and manufacturers often *discourage* the use of refills for such products. Printer cartridges and disposable batteries can be easily refilled or recharged, respectively, and can reduce resource consumption as well as the price of the product. However, as the economy of a region/country improves, resource consumption is higher due to higher consumer spending levels and ‘natural or planned obsolescence’ by manufacturers, institutions, and businesses (Jena and Goel 2015). Most white goods manufacturers have a tendency to produce goods with shorter service lives leading to more waste generation. This natural tendency has to be restrained by greener policies by governments and consumer will power. Examples of consumer goods that are being designed for shorter service lives include computers, cell phones, clothing, electrical and electronic appliances (white goods) and motor vehicles.

2.1.5 Material Selection and Durability

From an environmental standpoint, it is important to select materials and processes that will allow the components of the products to be reused or recycled easily. For example, it is possible to design car interiors with easy to disassemble and recyclable plastics as is the case with BMW and Volkswagen in Germany (Masters 1998). Today, the best management practices for dealing with e-waste are to recycle plastics from computers and metals from printed circuit boards.

Minimizing environmental impacts can entail substituting one material for another more environmentally benign option. This may at first be a more expensive proposition but the long-term benefits can be enormous. A case in point is the use of steel, lead and copper telecom cables by AT&T in the 1950s. Lead was replaced by polyethylene in the 1980s and fiber-optic cables replaced copper cables in the following decade, leading to large savings in lead, copper and energy use. Wireless technologies are another step in the same direction since they reduce resource consumption and eliminate destructive digging and defacing of roads, pavements and buildings. Today, cast iron pipes in water supplies are largely being replaced by plastic pipes due to their greater durability and fewer problems of corrosion and leakage. It is likely that mercury-free thermometers and lights like light-emitting diodes (LEDs) will be common products in the future since they are already available but presently not cost-effective in comparison to fluorescent lights.

Improving material efficiency is another aspect of green design. An example of this is the improved efficiency of lead-acid car batteries, which provide the same performance with smaller amounts of lead. Similarly reducing the weight of packaging or using new or different packaging materials is another method for reducing waste generation.

2.1.6 Process Management

Process management, also called environmental auditing, is a method of accounting for all inputs of raw materials and energy, and outputs of products and waste. Inefficiencies in the system (manufacturing processes) can be identified easily and the process made more efficient. This is somewhat similar to life-cycle assessment, where the same is done for a product rather than a process. Examples of improvements in process management are replacement of old parts like motors with more efficient ones; plugging leaks, using more fuel-efficient systems; better materials management and use of sensor-based, and high-efficiency lighting systems.

2.1.7 Distribution

Methods of distributing a product also determine the extent of waste generation. Packaging methods and transportation costs and their associated environmental impacts and energy requirements are major factors that can be improved to reduce waste generation. Transportation costs depend on the method of shipping (road, rail, sea or air), type of product and packaging required, and distance. A comparative cost analysis (direct and indirect or environmental costs) of all transportation options is necessary before choosing the best option. Use of recycled materials for packaging is another effective option for waste reduction. One of the simplest examples of reducing resource consumption and energy usage is the supply of domestic cooking gas by pipeline rather than gas cylinders.

2.1.8 Policy

Many policy initiatives have been taken in developed countries to reduce waste generation. Return policies for products like household appliances and automobiles and their packaging have been enforced in Germany while these have been adopted voluntarily by large corporations in the USA and India. Tax incentives are another option used by governments to make environment-friendly products comparable with similar products in the market. Consistent and standardized labeling and a credible authority for implementing these are another method of promoting waste reduction. A recent example is the energy efficient labeling system that is now being implemented in India by the Bureau of Energy Efficiency (BEE) and should lead to energy savings and environmental benefits for consumers and society. A similar system for products is required to standardize their net impacts on the environment and provide consumers with information about how ‘green’ the product is.

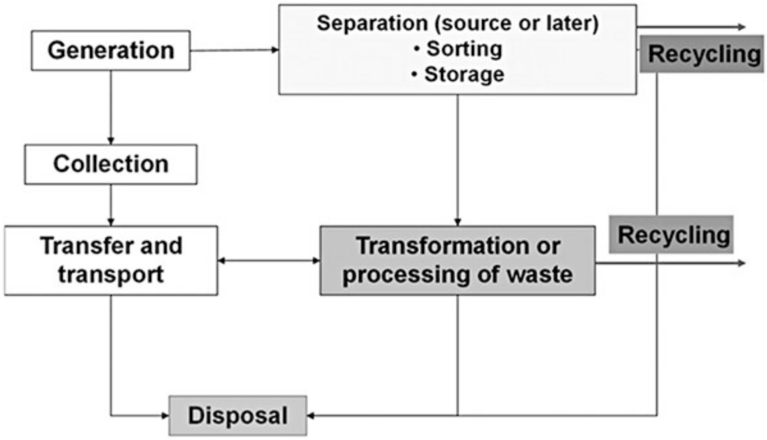


Fig. 1.5 Activities in municipal solid waste management systems

2.2 *Functional Activities in Municipal Solid Waste Management*

Figure 1.5 depicts the major functions or activities that are essential for municipal solid waste management (MSWM) and their relationship to each other.

2.2.1 Generation

In general at the household level, waste that is generated is separated as recyclables and disposables – and is defined as 'separation at source'. Recyclables are stored and kept separately for selling to kabadiwalas (scrap dealers in India), or recycling businesses.

Per capita MSW generation rates were estimated to vary between 0.2 and 0.87 kg/cap-d in India in 2011 with an average generation rate of 0.5 kg/cap-d (Annepu 2012). Most of the MSW generated (72.5%) in India comes from Class I or larger cities. Per capita waste generation rates are known to be correlated with income levels, both at the individual and country or regional levels (Hoornweg and Bhada-Tata 2012; Goel 2008). Per capita MSW generation rates in Asia have plateaued at values close to 1.0 kg/cap-d while those in developed European countries and USA have gone up to 2.0 kg/cap-d.

The success of many treatment methods noted later in this section is dependent on separation of waste at source into 'biodegradable' and 'other or mixed' fractions (Hazra et al. 2013). Separation into biodegradable and other fractions is rarely practiced in India and treatment methods like composting, incineration and biogas generation whose success depends on this type of source separation tend to fail in India. In contrast, separation of biodegradable and non-biodegradable materials is common in developed nations accounting for the success of their centralized treatment systems.

In urban areas, various sources of waste can be identified and include residential, commercial, industrial, municipal, institutional sources and construction and demolition activities. While generators of other categories of solid waste like biomedical, hazardous, batteries and flyash are held responsible for taking care of the waste generated, municipal solid waste regulations in India do not hold the generator responsible for taking care of the waste generated. The urban local body (ULB) is held responsible for all activities pertaining to managing this waste.

2.2.2 Segregation and Recycling

Waste collected can be segregated either at source or at any later stage of collection or transportation. In general, households and small businesses in India segregate (or separate) waste at source. All waste materials that are recyclable/saleable like paper, plastic, metal and glass are sold by householders and business people to recyclists (or recyclers) or kabadiwalas, who move from door-to-door buying these waste materials. A large, informal but highly organized network of recyclists and businesses has evolved over the years to make this a highly efficient and financially viable method of recycling especially in developing countries. However, as standards of living increase, these financial incentives become less significant or in many cases are no longer financially viable. This leads to the conditions in developed countries where recycling in residential areas remains a voluntary exercise with no financial incentives.

Small amounts of recyclable materials that remain in the waste in India are collected by ragpickers at open dumps while those that are taken to the municipal treatment and processing facilities are segregated manually.

Segregation at source or at a materials recovery facility is generally done in developed countries especially for biodegradable and non-biodegradable materials.

Recycling of various materials is constrained by several major factors:

1. Economics
    (a) *Financial sustainability:* Sufficient income has to be generated in the recycling of various waste materials so that it remains a sustainable source of livelihood for those involved.
    (b) *Quality of recyclable materials:* Another economic issue is the quality of the materials that are to be recycled. For example, newsprint is easier to recycle, i.e., gives better monetary returns, compared to magazine paper. Newsprint is manufactured by physical pulping of woody materials and no chemicals are added in the process.[3] Magazine paper, on the other hand, goes through various physical and chemical processes where chemical agents like bleach

---

[3] https://en.wikipedia.org/wiki/Newsprint

are added to make it white and clay additives are added to make it glossy after physical pulping. The percentage of reusable pulp per unit weight of magazine paper is therefore, much less compared to newsprint. In other words, after use, the pulp available from newsprint is much higher in quality and quantity compared to that obtained from magazine paper.

(c) *Quantity of recyclable materials:* The quantities of recyclable materials have to be sufficient to ensure long-term financial viability. The best example of this issue is the refusal of recyclists in India to pick up polyethylene terephthalate (PET) bottles but not high density polyethylene (HDPE) bottles. The weight to volume ratio (specific weight) of PET is much less than that of HDPE. Therefore, the uncrushed PET bottles occupy more space (or volume) than they are worth in terms of weight of the material, making it financially unattractive to transport them to recycling centres/businesses.

2. Ability to meet specifications

   A major issue in the recycling industry is whether the recycled product can meet specifications and compete with products made from virgin materials. For example, recycled plastic cannot be used for food packaging due to the presence of pigments and other additives in it. Similarly, recycled paper is generally restricted in terms of uses since it cannot be used for printing, and other high-end purposes. It is generally used as art paper, for blotting purposes, and several low-end uses.

3. Convenience to sellers and buyers

   The recycling industry has a stronger presence in less developed countries compared to developed countries since there is a well- established network of recyclists and higher order businesses. The door-to-door collection of recyclables with financial incentives for sellers and buyers in India makes it extremely convenient for people to recycle waste materials. Easily accessible deposit boxes for used batteries, cell phones, light plastics, computers, printers, and other disposable white goods would help to reduce the burden of transporting these recyclables. Collection of large volumes or weights of these recyclable materials will also ease their recyclability in terms of quality, quantity and cost-effectiveness.

2.2.3 Collection

Disposable waste materials are collected and stored at home for pick-up by the municipal (or administrative) authorities or are deposited in large community vans, containers or bins. Collection efficiencies in India are extremely poor and range from 70 to 90% in major metropolitan cities and are below 50% in smaller cities (Department of Economic Affairs 2009). At the global level, high income countries have high collection efficiencies (>90%) and spend less than 10% of their MSWM budgets on collection. Most of their MSWM budgets are spent on processing and disposal (Hoornweg and Bhada-Tata 2012). In comparison, low- and middle-income countries have lower collection efficiencies and higher percent spending on MSW collection ranging from 50 to 90% of their MSWM budgets.

Waste can be collected from individual households by house-to-house collection or the residents may be required to bring their waste to large community bins from where the ULB arranges to pick it up. Both systems are followed in both developed and developing countries. The first method is possible where residential units are single household units while the latter is followed in high population density areas, especially large apartment buildings. Collection is generally weekly or at higher frequency (daily or more is desirable) and storage of waste becomes an essential part of the collection process. The design of collection bins, their storage capacities, and locations are dependent on the frequency of cleaning and the population to be served. Separate collection systems are required for wastes from large commercial, industrial and construction activities.

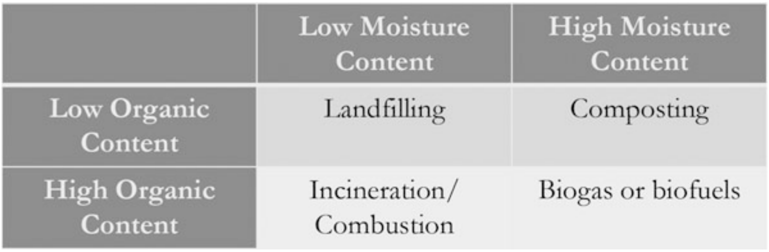
MSW in cities is collected by the respective municipalities and transported to designated disposal sites, which are frequently low-lying areas on the outskirts of the city without taking any precautions or operational controls. Most of the MSW generated in India is directly disposed of on land in an unsatisfactory manner. Such inadequate disposal practices lead to problems that will impair human and animal health and result in economic and environmental losses. Such examples can be seen in almost every city in the country. The limited budgets earmarked for the municipalities make them ill-equipped to provide for the high costs involved in the collection, storage, treatment and proper disposal of MSW. As a result, a substantial part of the MSW generated remains unattended at poorly maintained collection centres. The choice of a disposal site is more a matter of what is available rather than what is suitable.

2.2.4 Transfer and Transportation

Waste collected from containers or home bins is then transferred and transported to central facilities where appropriate processing or treatment methods can be applied. In developed countries, transfer stations are often combined with materials recovery facilities where different waste components are separated and sold for recycling.

Large urban areas may require transfer stations to improve collection and cost efficiency. Waste from community bins and individual homes is generally collected by small vehicles and deposited at transfer stations. From transfer stations, mixed waste can be segregated and taken either for further processing or for direct disposal to landfills.

The separated materials may include recyclables like paper, plastic and metals which can be processed and transformed for the manufacture of new products and these require separate facilities for that. Composting of the organic fraction of MSW is often done either at the transfer stations or at the disposal sites.



	Low Moisture Content	High Moisture Content
Low Organic Content	Landfilling	Composting
High Organic Content	Incineration/ Combustion	Biogas or biofuels

Fig. 1.6 Possible treatment options for different types of solid wastes

2.2.5 Processing or Treatment of Waste

Municipal solid waste treatment facilities have been setup in most large metropolitan centres in India. The emphasis in setting up these facilities has been to create technically and financially self-sustainable treatment plants. Several methods for treating MSW are available and are summarized in Fig. 1.6. MSW in India, especially if it is unsegregated, tends to be low in organic content and highly variable in moisture content depending on weather conditions (Kumar and Goel 2009). For example, samples collected from open containers in the monsoon have very high moisture content but those collected in other seasons may not have high moisture content.

For wastes with low organic and low moisture contents, the only option is landfilling. This applies to waste that is predominantly inert material like soil and dirt. For wastes with high organic and moisture contents, biogas or biofuel generation is the best treatment strategy since these two factors are necessary for biological processing, especially under anoxic (anaerobic) conditions. Wastes with relatively low or medium organic content but high moisture content are best composted under aerobic conditions while wastes with low moisture content but high organic content can be incinerated or combusted under controlled conditions.

The most popular treatment methods in India are composting (mainly windrow) and vermi-composting (Annepu 2012). For every 100 kg of raw material (mixed MSW) used for composting, compost generated was 6.5 kg. Currently, there are at least 70 composting plants in India (Kumar et al. 2008). Of these, 57 have a capacity greater than 200 ton/day and a total compost generating capacity of 4361 ton/day. It is estimated that 6% of the total urban MSW generated in the country is composted (Department of Economic Affairs 2009). Compost derived from mixed MSW is of low quality and contains toxic heavy metals in higher than admissible concentrations (Annepu 2012). In a study conducted to evaluate compost quality, 36 samples from 29 cities in India were taken and most samples were found to be outside acceptable limits based on the Fertilizer Control Order, 1985 (Saha et al. 2010). The only samples that met standards were from composting plants where the raw material was segregated at source.

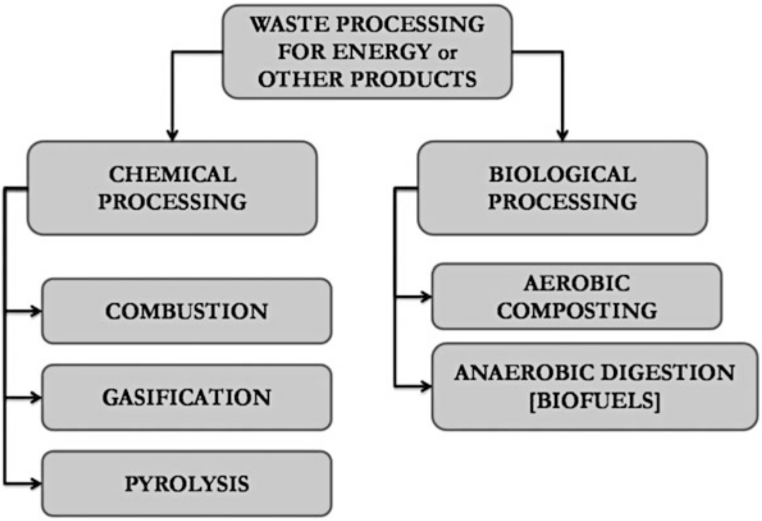


Fig. 1.7 Waste-to-Wealth (WTW) conversion processes

Waste-to-Wealth (WTW) Conversion

A major global trend is the use of WTW methods for MSWM. WTW methods include processes for generating energy (Waste-to-Energy, WTE) or useful end products like compost. In a time of growing energy needs and high costs of energy, WTE represents an additional renewable energy source and one that is carbon-neutral or results in reduction of GHG emissions. Waste can be converted to energy either chemically or biologically by several methods as shown in Fig. 1.7.

Chemical methods for WTE include combustion or incineration, gasification and pyrolysis where the objectives in MSWM are reduction in weight or volume of waste generated and generation of energy or other conversion products (Tchobanoglous et al. 1993).

Incineration is done by providing excess oxygen or air (based on stoichiometric requirements), gasification by providing sub-stoichiometric quantities of air or oxygen and pyrolysis is done in the absence of air. Incineration can reduce volume of MSW by 80–90% depending on the nature of the source material and energy can be utilized in the form of electricity or steam. It is a waste-to-energy option that has been used successfully in many countries for municipal solid waste management and is becoming increasingly popular. However, long-term success under Indian conditions has not been proved, mainly due to the need for and absence of air pollution control equipment. The minimum calorific value recommended for combustion-based WTE is 1790 cal/g. However, mixed MSW in India generally has low calorific value (average of 1751 cal/g) and high moisture content (average 47%) which makes combustion or incineration a difficult proposition. On the other hand, in European countries where land is becoming scarce, this is becoming an increasingly popular treatment strategy (Annepu 2012). The costs of incineration are estimated to be $\geq$3 times more than landfilling, making landfilling the most preferred option even in developed countries where land area is still available (Hoornweg and Bhada-Tata 2012).

Gasification results in the production of a usable fuel – synthetic gas (syn gas) which is a combination of H_2 and CO with small amounts of methane and carbon dioxide. Pyrolysis can be used to generate pyrolysis oil or a gas with similar composition as syn gas. Recent estimates show that the energy recovery potential from MSW alone in India is 1460 MW while the current installed capacity is only 24 MW (Kalyani and Pandey 2014).

Waste-to-energy methods like biogas generation are applicable only to agricultural and food processing waste and have not had commercial success with mixed municipal solid waste mainly due to lack of separation at source. It is estimated that one cubic metre of biogas can be converted to 1.5 kW of electricity (Annepu 2012).

2.2.6 Disposal

After most of the waste has been treated and compost or energy has been derived, the remaining material has to be landfilled. The Netherlands has adopted a treatment and disposal strategy of recycling, composting and waste-to-energy conversion so that the amount of MSW that is sent for landfilling is nearly zero (Annepu 2012). Waste materials can be reused, recycled, incinerated or landfilled. The latter two options are the final disposal options with ash from the incineration process also requiring landfilling. In countries like Australia, Canada and the USA where land is available in plenty, landfilling has been the method of choice for disposal of waste. However, greater understanding and cost of landfilling has now made countries like the USA move away from this option resulting in a significant decline in the number of landfills over the last few decades (USEPA 2003). The number of landfills in 1988 in the USA was 7924 and dropped to 1767 in 2002.

Indian regulations require that only non-biodegradable materials should be landfilled. Further, biodegradable materials should be separated at source and diverted for composting, anaerobic digestion or incineration. The market share of different MSWM technologies in India was estimated to be composting (50%), anaerobic digestion (30%), pelletization (10%) and sanitary landfilling (10%) (Singh et al. 2011). Financial resources for better MSWM are necessary and current budgetary allocations are obviously insufficient for achieving higher performance. Currently, municipalities are dependent on property and other taxes for their revenues which are generally insufficient for providing the required level of municipal services. There is sufficient evidence that people are willing to pay more for better services (Hazra et al. 2013).

3 Recommendations for MSW Management

1. With India's urban population increasing at an average annual rate of 3%, total solid waste generation rates are going to increase at a much greater rate with an economy growing at the rate of 5–10% in the last 3–4 decades. Source reduction and implementation of the 4Rs is an essential part of integrated solid waste management and needs all stakeholders – residents, businesses and administration to work together towards it.
2. The success of technologies like composting, anaerobic digestion and incineration depends on source separation into 'biodegradable' or 'organic' and other fractions. This will require public awareness campaigns to educate people and businesses about the need for doing so.
3. Given the high population density, increasing urban population and MSW generation, sanitary landfilling is going to become a prohibitively expensive proposition for the country in the future. The untapped potential in WTE needs to be exploited to the fullest extent, which means that investment in terms of financial and technical resources for developing waste-to-energy systems is essential for the future.

4 Hazardous Waste Management

Hazardous waste, also called industrial or chemical waste, has been around since the beginning of the Industrial Revolution. The introduction of synthetic organic compounds (SOCs) into the market and from there into the environment, and processes which increased the amount of resources consumed resulted in more products and better living standards for growing populations. A major consequence of this was an increase in the generation of pollutants that spread through air, water, soil and sediments and eventually contaminated the entire food web.

What makes 'hazardous waste' particularly hazardous is its 'recalcitrant and xenobiotic' nature. Many of these compounds are considered recalcitrant because it is difficult to break these compounds down into simple products like carbon dioxide and water, especially under natural conditions. Xenobiotic compounds are those that are 'alien' to the living environment they were introduced into and there are very few natural pathways for breaking down some of these recalcitrant compounds.

A chronological list of important events that have drawn attention to hazardous materials and waste is noted here:

1945 Radiation from two atomic bombs dropped over Hiroshima (August 6) and Nagasaki (August 9). Linkage between radiation and acute as well as chronic health effects became apparent.

1958 Linkage was suspected between the discharge of methyl mercury along with wastewater from a fertilizer manufacturing company (Chisso

Corporation) in Japan's Minamata Bay and a disease affecting the central nervous system. Forty patients were identified of whom 14 had died. Others affected included children, women, cats and birds and it was concluded that the disease was due to food poisoning probably associated with shellfish and fish contaminated with heavy metals including methyl mercury.[4]

1962 Publication of *Silent Spring* by Rachel Carson in the USA. The book was a milestone in drawing the world's attention to the negative environmental impacts of the use of synthetic organic compounds, especially pesticides.

1970 The United States Environmental Protection Agency, USEPA was set up with the mandate to provide a cleaner and healthier environment for the American people.

1976 Passage of the Resource Conservation and Recovery Act by the USEPA led to regulations and management of hazardous or industrial wastes in particular in the USA.

1980 Passage of the Superfund Act (Comprehensive Environmental Response, Compensation and Liability Act) for remediating contaminated sites around the USA and assigning financial responsibilities for cleanup.

1984 (2–3 December) – Methyl Isocyanate (also called phosgene) gas was released from Union Carbide's fertilizer manufacturing plant in Bhopal, India. Official death toll was 2259. Several thousands were affected by permanently disabling injuries.

1986 An explosion and fire in the Chernobyl Nuclear Power Plant in Pripyat, Ukraine (26 April) released large quantities of radioactive particles into the atmosphere which spread over much of the western USSR and Europe. There were 31 fatalities, several acres of forest were destroyed and radiation effects leading to cancer continue to be evaluated.[5]

1989 Notification regarding Hazardous Waste (Management and Handling) Rules in India.

1992 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, an international treaty to reduce movement of hazardous waste between nations and to prevent its transfer from developed to less developed countries became effective from 5 May 1992. As of January 2015, 182 countries are parties to the convention. Haiti and the USA are the only countries that have not ratified the convention.[6]

These events have made it clear to the international community that hazardous waste management is essential since:

---

[4] https://en.wikipedia.org/wiki/Minamata_disease

[5] https://en.wikipedia.org/wiki/Chernobyl_disaster#Radioactive_release

[6] https://en.wikipedia.org/wiki/Basel_Convention

(a) Exposure to hazardous material can result in short-term and long-term health problems,
(b) Long-term damage is likely to the environment and resources like water, sediment, soil and air,
(c) Bioconcentration of some hazardous or toxic compounds can lead to damage to biota and human health, and
(d) Closure and reclamation of old and defunct contaminated industrial sites is required.

4.1 Definitions of Hazardous Waste

Hazardous wastes are defined as such if they have any one or more of the following characteristics:

(a) *Ignitability:* If the waste material is likely to catch fire in the process of transport, storage, treatment or disposal, then it can be identified as hazardous waste. Examples include oils, solvents, flammable gases like methane; flammable compressed gas, and strong oxidizing agents. This definition also includes liquids with flash points < 60 °C.

    If the material is not liquid under standard temperature and pressure but can cause fire due to friction, absorption of moisture, or spontaneous chemical reactions, it is also defined as an ignitable substance.
(b) *Reactivity:* Chemically unstable waste materials are defined as reactive and therefore, hazardous. This includes materials that have extremely fast reaction rates which can result in explosive conditions at any stage in the management cycle; if it can undergo violent change with or without detonation; if it reacts violently with water and forms a potentially dangerous mixture with water; if it is explosive or toxic; cyanide or sulfide-bearing;waste that can release toxic gases, vapours, fumes within a pH range of 2–12.5 are all included in this definition.
(c) *Corrosivity:* Waste materials with very low pH (<2) or very high pH (>12.5) are considered corrosive and therefore, hazardous.
(d) *Toxicity:* Any material that is poisonous at some concentration is defined as toxic. For hazardous wastes, many toxic substances may be present in a mixture. Two common test procedures recommended by the USEPA for determining the toxicity of a mixture of materials are:

    (i) Extraction Procedure (EP) toxicity test: This test is no longer in use since it has a very small number of contaminants in its list and the maximum concentrations are no longer acceptable. Eight toxic heavy metals: arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver, and six pesticides Endrin, Lindane, Methoxychlor, Toxaphene, 2,4-D and 2,4,5-TP Silvex have been listed.

(ii) Toxicity Characteristics Leaching Procedure (TCLP): TCLP replaced the EP toxicity test in 1990. This test is used to determine the leaching potential of liquid or solid mixtures of toxic materials. TCLP analysis simulates landfill conditions. Over time, water and other liquids percolate through landfills. The percolating liquid often reacts with the solid waste in the landfill, and may pose public and environmental health risks because of the contaminants it absorbs. TCLP analysis is used to determine which of the contaminants identified by the United States Environmental Protection Agency (EPA) are present in the leachate and their concentrations.

(e) *Radioactivity:* Unlike reactivity which refers to the instability of an atom or molecule, radioactivity refers to the instability of the nucleus which results in spontaneous breakup of the nucleus of the atom. As long as the number of protons (Z) is low, and the number of neutrons (N) is approximately equal to Z, the nucleus is stable, i.e., $Z/N \leq 1$ for N or $Z \leq 20$. As the number of protons (Z) increases, more neutrons (N) are required to maintain the stability of a nucleus. At $N > 83$, repulsive forces within the nucleus dominate and the nucleus becomes unstable or naturally radioactive. Any element can be made 'artificially radioactive' by shooting a beam of neutrons at it.

All radioactive materials may emit any or all of the following three types of radiation:

Alpha radiation: Emission of helium nuclei, i.e., two neutrons, two protons,

Beta radiation: Emission of electrons released from a radioactive nucleus, and

Gamma radiation: Electromagnetic radiation that travels at the speed of light; it has no particles unlike the other two types of radiation.

(f) *Infectivity:* Waste containing viable microbes or their toxins that are known to cause diseases in animals or humans are considered infective and therefore, hazardous. An example of such waste is biomedical waste.

(g) *Phytotoxicity:* Any material that has a toxic effect on plants is considered phytotoxic and therefore, hazardous.

(h) *Mutagenicity:* Any material or compound that causes change in the genetic structure (DNA) of an organism is considered to be *mutagenic* or capable of causing mutations. While there is a natural or background level of mutational frequency in every organism, the presence of mutagenic compounds leads to a significant increase in mutational frequency.[7] Most mutations are not capable of propagating themselves, i.e., they die naturally. However, those that do propagate themselves result in the formation of tumors and such compounds are termed *tumorigenic*. Tumors can be benign or malignant. If the tumor is malignant, it is termed cancer and the causative agent or compound is termed *carcinogenic*.

---

[7] https://en.wikipedia.org/wiki/Mutagen

(i) *Cytotoxic:* Materials that cause damage to an organism's cells or tissue are termed cytotoxic.

(j) *Teratogenic:* If a substance affects the development of an embryo or fetus resulting in developmental defects such as growth retardation, malformation, functional defect or death, the causative agent or compound is termed *teratogenic*.[8]

4.2 Categories of Hazardous Waste

Hazardous waste can be categorized based on its sources or based on its chemical constituents.

4.2.1 Hazardous Waste Categories Based on Sources

Major sources and types of hazardous waste are:

(i) Chemicals manufacturing and ancillary industries
(ii) Nuclear power plants
(iii) Biochemical and biomedical industries
(iv) Sludges from water, wastewater treatment plants and air pollution control equipment in factories and industries
(v) Household hazardous waste, and
(vi) Electronic waste

It is important to note that hazardous waste sources can be intentional or accidental releases of waste and in all cases containment, treatment and disposal are required.

4.2.2 Hazardous Waste Categories Based on Chemical Constituents

The USEPA has categorized hazardous materials or wastes as shown in Table 1.1.[9] A more exhaustive list of examples is provided in the referenced footnote.

---

[8] https://en.wikipedia.org/wiki/Teratology

[9] http://www.frtr.gov/matrix2/top_page.html

Table 1.1 Hazardous waste categories, their sites and some examples

Hazardous waste category	Possible sites	Examples
Non-halogenated Volatile Organic Compounds (VOCs)	Chemical manufacturing plants or disposal areas, electroplating/metal finishing shops, hangars/aircraft maintenance areas, landfills and burial pits, leaking storage tanks, radioactive/mixed waste disposal areas, oxidation ponds/lagoons, paint stripping and spray booth areas, pesticide/herbicide mixing areas, solvent degreasing areas, surface impoundments, and vehicle maintenance areas.	Ethanol, methanol, carbon disulphide, acetone, etc.
Halogenated Volatile Organic Compounds (HVOCs)	As above	Trichloroethylene (TCE), chloroform and dichloromethane
Non-halogenated SVOCs	As above	Non-halogenated pesticides like parathion, malathion; PAHs like naphthalene and anthracene, etc.
Halogenated Semi-Volatile Organic Compounds (SVOCs)	As above and wood preserving sites	Pesticides like DDT, Endrin, Endosulfan and their degradation intermediates
Fuels	Aircraft areas, burn pits, chemical disposal areas, contaminated marine sediments, disposal wells and leach fields, firefighting training areas, hangars/aircraft maintenance areas, landfills and burial pits, leaking storage tanks, solvent degreasing areas, surface impoundments, and vehicle maintenance areas.	Petroleum compounds like benzene, toluene, ethyl benzene, xylene, etc.
Inorganics	Artillery and small arms impact areas, battery disposal area, burn pits, chemical disposal areas, contaminated marine sediments, disposal wells and leach fields, electroplating/metal finishing shops, firefighting training areas, landfills and burial pits, leaking collection and system sanitary lines, leaking storage tanks, radioactive and mixed waste disposal areas, oxidation ponds/lagoons, paint stripping and spray booth areas, sand blasting areas, surface impoundments, and vehicle maintenance areas.	All metals and their compounds, cyanide, fluorine, asbestos, etc.

(continued)

Table 1.1 (continued)

Hazardous waste category	Possible sites	Examples
Radionuclides	Radioactive and mixed waste disposal areas	Uranium, thorium, cesium, radon, radium, carbon-14, etc.
Explosives	Artillery/impact areas, contaminated marine sediments, disposal wells, leach fields, landfills, burial pits and TNT washout lagoons	TNT, RDX, nitroaromatics, etc.

These categories are often used to design and evaluate treatment options.

4.3 Treatment and Management

Hazardous waste is generated by several sources as mentioned in Sect. 4.2.1. Treatment and management of hazardous waste is required for the following situations:

(a) Old and defunct contaminated sites and accidental releases of hazardous materials, and
(b) Treatment and management of hazardous waste from current sources (intentional releases)

4.3.1 Site Remediation and Accidental Releases

Developed countries and many less developed countries are now dealing with the problem of rejuvenating old, defunct industrial sites. The USA now has a Brownfield programme that provides funds and technical assistance for remediating and reusing these sites and bringing them back into clean use. Further, accidental releases of pollutants need to be controlled and managed effectively.

The first step in managing site remediation or accidental releases is controlling the source of pollution followed by some form of treatment for the contaminated media: water (surface and ground water), soil, sediment and air.

Source Control Containment methods adopted to control the source of pollution depend on the nature of the pollutant, environmental media affected, quantity and concentration of pollutant released into the environment, and the factors affecting the spread of the contaminant. For accidental releases or long-term release of pollutants into groundwater, a field of extraction and injections wells can be developed to contain the spread of the pollutant plume and in some cases, to pump and treat the polluted water (Masters 1998). Population relocation may be necessary as part of the containment phase of an accidental release or site remediation.

After containment, the pollutants have to be treated to a level of acceptable risk or lowest achievable concentration depending on the treatment strategy adopted.

Treatment can be done *in situ* or *ex situ*. Monitoring is required during and after treatment to ensure that maximum concentrations levels of the pollutants are not exceeded.

In Situ Treatment Methods Several *in situ* methods can be used for site remediation and include stabilization/solidification, bioremediation, thermal desorption, chemical treatment, soil vapour extraction, flushing, vitrification and others (LaGrega et al. 2001).

Ex Situ Treatment Methods Similarly, several *ex situ* methods can be used and include stabilization/solidification, incineration, bioremediation and thermal desorption.

Groundwater Treatment Contaminated groundwater can be treated *in situ* or *ex situ*. *In situ* methods tend to be less expensive than *ex situ* methods. Examples of *in situ* and *ex situ* methods are noted here.

In Situ Air sparging, bioremediation, chemical treatment, permeable reactive barrier and multi-phase extraction.

Ex Situ Pump and treat.

Where the extent or concentration of pollutant is relatively low or the groundwater is not going to be used for potable purposes, the easiest remediation strategy to adopt is ‘natural attenuation’. Monitoring of pollutant concentration is the only requirement for natural attenuation.

4.3.2 Treatment, Storage and Disposal Facilities (TSDFs)

Treatment, storage and disposal facilities (TSDFs) are required in countries like India and the USA as part of hazardous waste management of any sources (past, current or future). The latest report shows that India generates 6.2 million metric tons of hazardous wastes per annum (CPCB 2010). Of this waste, 3.1 million metric tons is recyclable and 2.7 million metric tons is landfillable. The rest is incinerable. There are currently, 26 TSDFs in India spread over 12 States and one Union Territory.

A major issue in the operation of TSDFs is waste compatibility. USEPA under RCRA has well-defined procedures for determining whether one waste can be mixed with another safely. A RCRA compatibility chart that shows the consequences of mixing waste from one group with another is provided in Appendix A. The reader is referred to original documents for greater clarity.

The procedure for acceptance of waste followed by Indian TSDFs along with recommended treatment technologies has also been defined recently and the document is available from CPCB’s website (CPCB 2010).

5 Concluding Remarks

In summary, it is clear that solid and hazardous waste generation is increasing exponentially all over the world due to increasing population and higher per capita resource consumption. While developed countries have reasonably sustainable infrastructure in place for handling these types of wastes, less developed countries have a long way to go. The search for waste-to-wealth treatment technologies and carbon-neutral processes and solutions remains a global challenge.

References

Annepu, R.K., 2012. Sustainable Solid Waste Management in India. Department of Earth and Environmental Engineering at Columbia University.

CPCB, 2010. Protocol for Performance Evaluation and Monitoring of the Common Hazardous Waste Treatment Storage and Disposal Facilities including Common Hazardous Waste Incinerators.

Department of Economic Affairs, 2009. Position paper on the Solid Waste Management Sector in India. Ministry of Finance, Government of India.

Goel, S., 2008. Municipal Solid Waste Management (MSWM) in India: A Critical Review. *Journal of Environmental Science and Engineering, NEERI*, **50(4)**, 319–328.

Hazra, T., Goel, S. and Maitra, B., 2013. Willingness-to-pay for solid waste management service attributes: Kolkata Municipal Corporation area, India, as a case study. *International Journal of Environment and Waste Management*, **12(4)**, 406–421.

Hoornweg, D., & Bhada-Tata, P, 2012. *What a Waste: A Global Review of Solid Waste Management. Urban Development Series Knowledge Papers*. Washington DC, USA. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/25270340

Jena, S. and Goel, S., 2015. E-waste generation in an academic campus: IIT Kharagpur as a case study. *Pollution Research*.

Kalyani, K.A. and Pandey, K.K., 2014. Waste to energy status in India: A short review. *Renewable and Sustainable Energy Reviews*, **31**, 113–120 doi:10.1016/j.rser.2013.11.020.

Kumar, K. N., & Goel, S., 2009. Characterization of Municipal Solid Waste (MSW) and a proposed management plan for Kharagpur, West Bengal, India. *Resources, Conservation and Recycling*, **53**(3), 166–174. http://doi.org/10.1016/j.resconrec.2008.11.004.

Kumar, S., Bhattacharya, J.K., Vaidya, A.N., Chakrabarti, T., Devotta, S. and Akolkar, A.B., 2008. Assessment of the Status of Municipal Solid Waste Management in Metro Cities, State Capitals, Class I Cities and Class II Towns in India: An Insight.

LaGrega, M., Buckingham, P. and Evans, J., 2001. Hazardous Waste Management. McGraw Hill International.

Masters, G., 1998. Introduction to Environmental Engineering and Science. Prentice Hall, NJ, US.

Masters, G. and Ela, W., 2008. Introduction to Environmental Engineering and Science. Prentice Hall, NJ, US.

Pappu, A., Saxena, M. and Asolekar, S.R., 2007. Solid wastes generation in India and their recycling potential in building materials. *Building and Environment*, **42(6)**, 2311–2320. doi:10.1016/j.buildenv.2006.04.015.

Saha, J.K., Panwar, N. and Singh, M.V., 2010. An assessment of municipal solid waste compost quality produced in different cities of India in the perspective of developing quality control indices. *Waste Management (New York)*, **30(2)**, 192–201. doi:10.1016/j.wasman.2009.09.041.

Singh, R.P., Tyagi, V.V., Allen, T., Ibrahim, M.H. and Kothari, R., 2011. An overview for exploring the possibilities of energy generation from municipal solid waste (MSW) in Indian scenario. *Renewable and Sustainable Energy Reviews*, **15(9)**, 4797–4808. doi:10.1016/j.rser.2011.07.071.

Tchobanoglous, G., Theisen, H. and Vigil, S., 1993. Integrated Solid Waste Management: Engineering Principles and Management Issues. McGraw Hill International, Singapore. Civil Eng Series Singapore.

USEPA. 2005. *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2003*.

Chapter 2
Moving Towards a Circular Economy in Solid Waste Management: Concepts and Practices

Maria Isabel Dumlao-Tan and Anthony Halog

> *The paradox of life lies exactly in this: its resources are finite, but it itself is endless. Such a contradictory state of affairs is feasible only because the resources accessible to life can be used over and over again.*
>
> *—I.I. Gitelson, author of the book "Man-made Closed Ecological Systems"*

1 Introduction

Wastes are defined as those materials, substances, objects and products that are no longer of use to the consumer in terms of its original purpose, and are then disposed to the environment, usually as prescribed by the law. Based on a study in 2012, global municipal solid wastes (MSW) are expected to increase to approximately 2.2 billion tonnes per year in 2025 (Hoornweg and Bhada-Tata 2012). Wastewater, on the other hand, is also considered a global problem with many regions experiencing different issues: from water disease-related deaths in Africa and Asia to eutrophication in China and Europe (GEO5 2012). Another waste, for example, emissions of carbon dioxide (CO_2) from anthropogenic sources, is reported to be one of the major causes of increase in the global mean temperature. These temperatures are expected to increase by 1.8–4.0 °C between 1980 and 2100 (IPCC 2007). Aside from being considered as consumers of environmental resources, mankind is also considered as producers or generators of wastes which has put a strain on the environment. When the environment is affected, this poses a question to the finiteness of our resources. This chapter focuses on solid wastes, waste management, and the significance of a Circular Economy (CE) to solid waste management.

M.I. Dumlao-Tan (✉) • A. Halog
School of Earth and Environmental Sciences (SEES), The University of Queensland,
Brisbane, QLD 4072, Australia
e-mail: dumlette@yahoo.com

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_2

1.1 Past, Current and Emerging Issues Related to Solid Wastes

Traditionally, solid wastes are discarded after use, and disposed to the environment. Treatment of solid wastes eventually evolved from a reactive approach to management of wastes. A similar linear economy model that was conventionally followed by manufacturers and industrial processes is described as the "take-make-dispose" approach. However, the improper disposal of solid wastes results in pollution, and causes diverse and adverse environmental and health effects. Historical cases of these effects include the Black Death in the mid-14th century in Europe, and the Payatas Dumpsite tragedy in 2000 in the Philippines. Our modern world will also have to address current and emerging issues related to solid wastes: the presence of nano-particles and nano-materials, marine debris such as the Great Pacific garbage patch, transboundary movement of hazardous wastes and e-wastes, increasing volumes of end-of-life products, urban mining, integration of the informal sector, and immigration (GEO5 2012). Special waste streams have also become significant such as hazardous wastes, electronic wastes, bio-medical wastes, and radioactive wastes. These events and issues warrant the establishment of appropriate solid waste management practices.

However, the definition of wastes as being unwanted is relative, and has different meaning for different people. One person's waste may be another person's useful material. Or a product such as a mobile phone that is already at the end-of-life for certain users can still be used by another user. These solid wastes can either be a resource or a pollutant, or both. For example, lead found in computer circuit boards can be recycled to recover the lead, or it can contaminate the environment if left untreated. There are local governments and businesses which have started to consider end-of-life products as secondary resources. For example, in recent years, e-wastes have been receiving attention as secondary sources of metals because they contain precious metals (e.g., gold, silver and palladium) and special metals (e.g. indium, selenium, tellurium, tantalum, bismuth and antimony). The concentrations of gold and palladium found in printed circuit boards (PCBs) of personal computers are 250 g/t and 110 g/t, respectively (Hagelüken 2005). In the recycling of mobile phones, 80% of the value of the materials is due to gold, followed by 10% from palladium and 7% from silver (Navazo et al. 2014). Likewise, in the same study by Navazo et al. (2014), an average tonne of used mobile phones represents a potential of 128 kg of copper, 0.347 kg of gold, 0.15 kg of palladium, 3.63 kg of silver, 15 kg of nickel, 6 kg of lead, 1 kg of antimony, and 10 kg of tin as well as other metals. Examples of other solid wastes and their potentially recoverable materials are shown in Table 2.1.

Thus, within the perspective of solid waste management, solid wastes can also be characterised by their pollution potential and resource potential. *Pollution potential* is defined as "an attribute of substances that degrade environmental quality if they are treated in an improper way...", whereas *resource potential* is

Table 2.1 Solid wastes and their potentially recoverable materials

Waste	Recoverable resource
Construction and demolition waste	Metals, wood, glass, plastics, paper and cardboard, stone, mortar, gypsum
E-wastes	Metals
Batteries, superconductors, motors and generators, phosphors in fluorescent lamps	Rare Earth Elements (REE)
Food wastes, food processing wastes	Biogas, soil conditioner, specialty chemicals (i.e., pectin from citrus peel, phenols from grapes, casein from milk by-products), animal feed or fish food
Cooking oils and fats	Biofuel
Clothing wastes	Nutrients, polyester, cellulose
Packaging wastes	Glass, plastic, paper and cardboard

Sources: Bermejo (2014), Ellen MacArthur Foundation (2013) and Schüler et al. (2011)

defined as "an attribute that substances, after they are properly treated, contribute to production by positive marginal productivity..." (Hosoda 2007).

1.2 Integrated and Sustainable Waste Management

In order to primarily eliminate or reduce the negative impacts of solid wastes to air, water and land environments, and to public health, proper solid waste management is needed for its generation, storage, collection, transfer and transport, processing and treatment, and disposal. Conventional solid waste management, especially in developed countries, was based on the use of technology. An integrated approach to solid waste management has been developed to address the need for inter-related management options at different habitat scales, of involvement of all stakeholders (government or non-government, formal or informal, profit or non-profit oriented), and of interactions with other urban systems (wastewater treatment, energy production, food production facilities) (Van de Klundert and Anshutz 1999). Based on the waste management hierarchy, integrated solid waste management also focuses on technological solutions for recycling, composting and energy recovery. In the 1990s, a holistic and comprehensive approach to solid waste management was developed to address sustainability (in terms of environmental, social and economic). Through the 2000s, the concept of integrated sustainable waste management (ISWM) has improved, and is used as a basis for solid waste management in developing countries. The core concept of ISWM is based on three dimensions in waste management: (1) the stakeholders, (2) waste system elements (all the elements of the waste management hierarchy), and (3) sustainability aspects (political, institutional, social, financial, economic and technical). The ISWM framework is represented by the "Two Triangles" (Fig. 2.1) (Wilson et al. 2013).

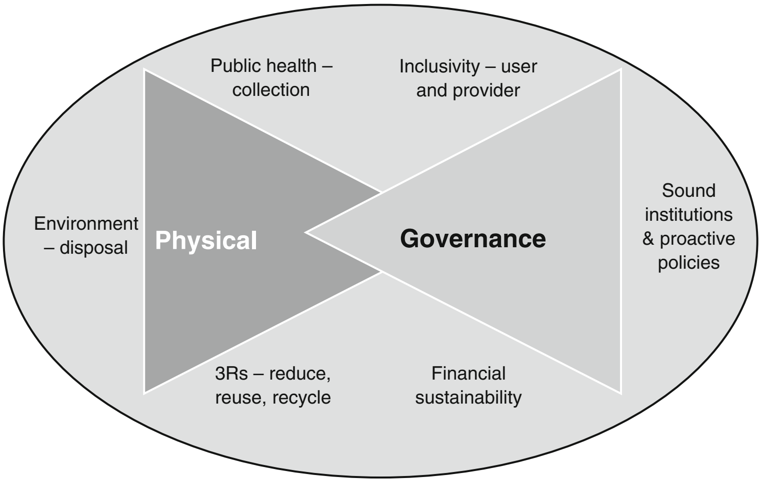


Fig. 2.1 Two triangles of ISWM (©David Wilson, Costas Velis, Ljiljana Rodic; Reproduced with permission)

The first triangle focuses on the three physical (hardware) components:

- Public health: maintaining healthy conditions in cities through a good waste collection service;
- Environment: protection of the environment throughout the waste chain, especially during waste treatment and disposal; and
- 3Rs or resource management: ‘closing the loop’ and returning both materials and nutrients to beneficial use, through preventing waste and striving for high rates of reuse, materials recycling and organics recovery.

The second triangle focuses on the governance (software) components:

- Inclusivity: providing transparent spaces for stakeholders to contribute as users, providers and enablers;
- Financial sustainability: being cost-effective and affordable; and
- A base of sound institutions and pro-active policies.

Looking at the ISWM framework, it has given equal importance to waste minimization, recycling and reuse, together with the other elements (collection, transfer, treatment and disposal). The 3Rs (reduce, reuse and recycle) remain major priorities for a good solid waste management. The 3R philosophy is also the core concept of an integrated resource management. Both ISWM and integrated resource management focus on the direction of implementing the 3Rs based on ‘closing the loop’, eco-design, recyclability of new products, and use of ‘circular economy’ philosophies (Wilson et al. 2013).

2 What Is a Circular Economy?

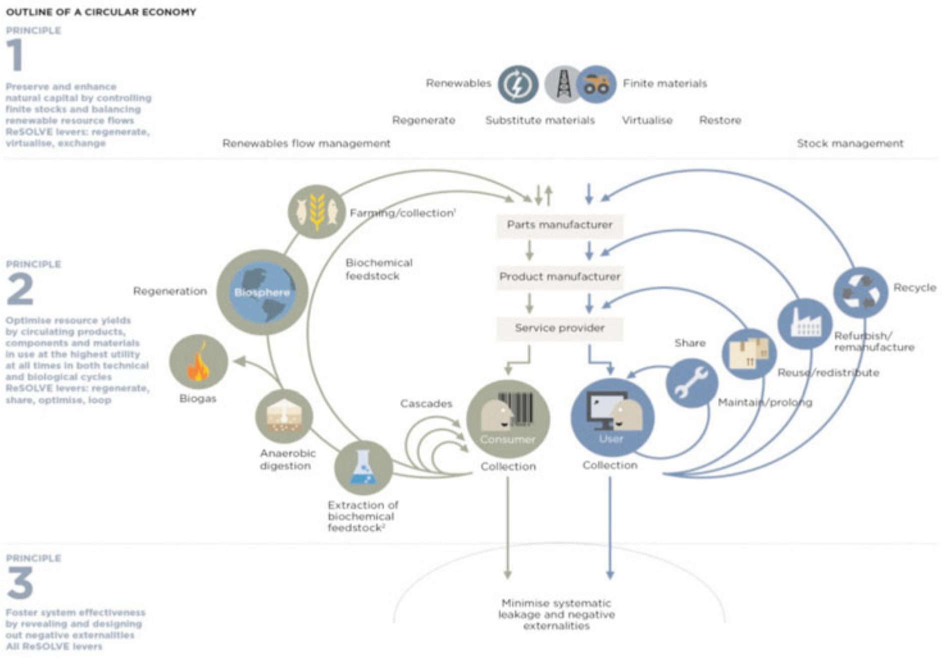
According to the Ellen MacArthur Foundation (EMF), Circular Economy (CE) is defined as "an industrial system that is restorative or regenerative by intention and design; it replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and within this, business models" (Ellen MacArthur Foundation 2016). A generalized illustration summarizes the guiding principle, and the circular loops for renewable and non-renewable materials (Fig. 2.2). The main objectives of the circular economy are to reduce wastage of resources (such as raw materials and energy), to decouple resource consumption from GDP growth, to reduce environmental impacts, and increase human well-being (including increasing employment) (CIRAIG 2015).

The main characteristics of CE can be summarized as: it functions with 'societies or industries that are imitating the behaviour of ecosystems'; it relies on a closed loop system; it is a paradigm shift from "cradle-to-grave" to "cradle-to-cradle", from disposability to restorability, from "take-make-dispose" to "take-make-recreate"; it puts more value on use rather than on consumption; promotes materials stewardship; it is focused on eco-effectiveness rather than on eco-efficiency; it is based on systems thinking; and it requires resources which are biodegradable and are possible for permanent reuse (Bermejo 2014; CIRAIG 2015; Florin et al. 2015; Ellen MacArthur Foundation 2016).

2.1 Principles and Scales in a Circular Economy

Principles The EMF illustration of CE is based on the sustainability concept through the recycling of materials, or "nutrients". Similar to ecological recycling where organic and inorganic matter are circulated in nature through uptake, digestion, release and storage for the production of living matter, the CE nutrients are cycled in specific patterns in a system of inputs and outputs. There are two CE nutrients: (1) biotic nutrients (which follow metabolic pathways of recycling by the biosphere; eventually they are returned to the soil as nutrients); and (2) technical nutrients (which can be infinitely recycled and reused without loss in quality) (CIRAIG 2015).

Scales or Spatial Levels CE can be applied at three spatial levels: (1) the *micro level* – individual enterprises or firms using cleaner production, (2) the *meso level* – also called the inter-enterprise level; the eco-industrial park level involving clustered or chained industries, and responsible supply chain, and (3) the *macro level* – also called the societal level; between production and consumption systems in regions, between industries and urban environment in an "eco-region" or municipality (CIRAIG 2015; Florin et al. 2015).



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

SOURCE: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

Fig. 2.2 Circular economy for renewable and non-renewable resources (Reproduced with permission from Ellen MacArthur Foundation 2016)

2.2 Business Models and System Theories for a Circular Economy

With the understanding that CE was initially developed as an economic imperative, there are five circular business models that can be applied at a company level (CIRAIG 2015):

1. The *Circular Supplies Model* is based on the cradle-to-cradle (C2C) concept that operates on a loop of renewable and/or biodegradable resource.
2. The *Resource Recovery Model* is based on the concept of industrial ecology and operates on the principle of converting wastes into inputs through linked product and industrial life cycles.
3. The *Product Life Extension Model* is based on the core principles of functional economy, and operates on the principle of repair, upgrade, remanufacture and remarketing of products for value retention.
4. The *Sharing Platforms Model* is similar to the collaborative consumption or the share economy concepts where high utilization rate of products or services is maximized through efficient sharing, distribution among users.
5. The *Product as a Service Model* is based on the functional economy principle, and operates by transforming consumers into users in a lease or pay-for-use economic arrangement.

The following discussion describes system theories that serve as core concepts of the business models, and their significance to CE. It also includes discussion of how elements of ISWM are integrated into the different system theories.

2.2.1 Cradle-to-Cradle (C2C)

Braungart and McDonough defined Cradle-to-Cradle (C2C) thinking in the 1990s as a nature-inspired, biomimetic design philosophy, or a “design framework that moves beyond the goal of only reducing an organization’s negative impacts (eco-efficiency) to provide an engaging vision for (stake-holders) to create a wholly positive footprint on the planet – environmental, social and economic (eco-effectiveness)” (van Dijk et al. 2014). The concept of eco-efficiency versus eco-effectiveness is best illustrated as “doing things right” (eco-efficiency) vs “doing the right thing” (eco-effectiveness). C2C aims for the products to have a positive environmental footprint instead of aiming for a reduction in negative impacts (i.e., reducing waste amounts or converting wastes into useful materials) (CIRAIG 2015; van Dijk et al. 2014). Rather, C2C is a system “powered by renewable energy in which materials flow in safe, regenerative, closed loops” (van Dijk et al. 2014). Thus, the C2C model can be operationalized using the ISWM elements involving the closed-loop system of manufacture, recovery and reuse that should enable a material (such as metals) to maintain its highest value through many product life cycles (Bollinger 2010). The end-of-life products obtain their resource potential through upcycling and "rematerialization" (rather than dematerialization).

2.2.2 Functional Economy

Stahel's definition of Functional or Performance Economy as a new business model with enterprises retaining ownership of long life-span goods combined with lower energy and materials demand for the production phase made possible by appropriate design (CIRAIG 2015). Its concept is also related to the Product Service System (PSS) defined as "a marketable set of products and services and capable of jointly fulfilling a user's need" (CIRAIG 2015). Functional Economy focuses on a looped economy, using waste prevention, refurbishment and reconditioning. Thus, in the context of ISWM, Functional Economy addresses maximization of resource potential of end-of-life products through maintenance, repair and/or remanufacturing of waste into new products resulting in an increase in wealth creation and increase in jobs, whereas it addresses minimization of pollution potential of the end-of-life products through reduction of resources consumption. In relation to CE, their common principle is the longevity and intelligent waste-as-input management (CIRAIG 2015).

2.2.3 Industrial Ecology

Industrial Ecology (IE) is defined as a conceptual framework, an implementation tool; and also called an industrial symbiosis wherein industrial facilities or companies work together in order for one's wastes or by-products to become raw materials for another (CIRAIG 2015). van Dijk et al. (2014) has summarized the principles, elements and strategies for Industrial Ecology in his literature review. To summarize from this review, the main principles of IE are: (i) reduce use or eliminate toxic waste products; (ii) design for environment; (iii) dematerialisation; (iv) substitution of scarce or hazardous materials; (v) repair, reuse, remanufacturing, and (vi) waste mining and (vii) develop more effective technologies to reduce resource consumption.

3 Applications of Circular Economy to Integrated or Sustainable Solid Waste Management

In the case of solid wastes, CE both aims to reduce pollution potential and maximize the resource potential of wastes. Thus, CE is not just a waste management imperative but also a system to link scarce resources and the economy (resource management). Using the functional elements of ISWM, recycling is the most used strategy in a circular economy; however we still need to minimize wastes and reduce the consumption of resources to achieve complete success in a circular economy (Bermejo 2014). One of the initial stages for fully implementing CE is the need for transition in waste management. Figure 2.3 represents the functional elements of ISWM (generation and storage, collection, transfer and transport, treatment and disposal), and the circular loops that can be applied (although not included, the concept should not disregard the significance of the six sustainability aspects: political, institutional, social, environmental, economic and technical; and the stakeholders).

Three categories of solid wastes are explored to demonstrate how CE can be applied to an integrated sustainable solid waste management system: construction and demolition wastes, hazardous wastes, and e-wastes. These categories were selected due to the nature of the resources used, and the wastes generated.

3.1 Gypsum from Construction and Demolition (C&D) Wastes

In developed countries such as European countries, the construction sector contributes significantly to the economy. For instance in EU, it corresponds to about 10% of its GDP. According to EU forecasts, it is predicted that the construction industry will have an annual growth rate of up to 3%. The European Commission has also established the “Construction 2020 Action Plan” in 2013 to ensure that the industry becomes more competitive and experiences sustainable growth. One of the objectives of the said plan is resource efficiency (GtoG report 2015). Construction activities from the construction of buildings and infrastructure to the total or partial demolition, renovation and maintenance of these infrastructures results in the generation of Construction and Demolition (C&D) wastes. C&D wastes are characterized by the presence of numerous materials: concrete, bricks, wood, glass, metal, plastics, solvents, asbestos, gypsum and excavated soil. It can constitute up to 50% of the total solid wastes generated in a country. According to an EU statistical report, in 2008, the construction sector accounted for 32.9% of the total wastes generated in the EU member states (Eurostat 2011). These wastes are considered important to waste management because they represent one of the heaviest and most voluminous waste streams. For resource management, it is of concern because of the increasing demand for raw materials in construction. Another issue to be considered is the presence of toxic substances (i.e., lead, asbestos, solvents) in buildings that could affect the recyclability of the wastes.

Gypsum products include plasterboard, building plaster, drywall, wallboard or sheet rock and gypsum blocks. It was reported in Australia that plasterboard waste in C&D waste stream ranges from 4 to 8%. In the US, a report indicated that drywall accounts for around 13.4% of the C&D waste. Gypsum can be recovered and recycled from these wastes. It is fully and eternally recyclable because its chemical composition does not change (GtoG Report 2015).

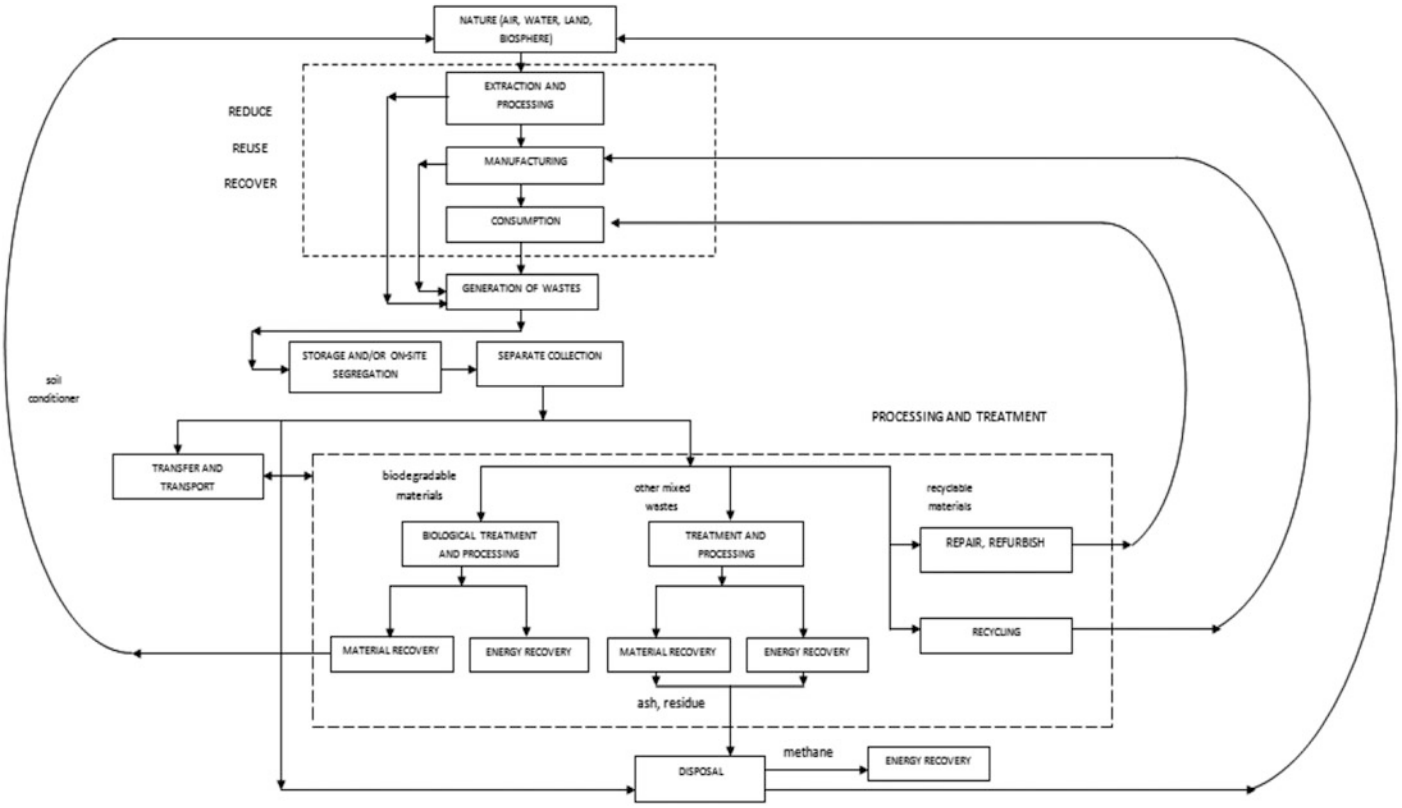


Fig. 2.3 ISWM functional elements and circular loops for circular economy

3.1.1 Which Model Works for This Waste?

A project funded by the European Commission was conducted in 2013–2015. It is called the GtoG project which covers the recycling of plasterboard waste for reintroduction of recycled gypsum into the manufacturing process (GtoG Report 2015). To achieve CE for the Gypsum industry with the demolition and recycling industries, a cradle-to-cradle (C2C) model was applied as shown in Fig. 2.4. The top part of the 'loop' illustrates the manufacture of gypsum products, followed by their use in production. The bottom half of the 'loop' shows how gypsum products can be recycled. It also involves the need for efficient value chain management in which the respective stakeholders participated to extract maximum value of gypsum from plasterboard waste.

- Deconstruction: Plasterboard at the demolition site was dismantled critically, expending effort, time and care. The wastes were separated properly with minimal damage to the waste plasterboard. These activities enable the plasterboard wastes to have high resource potential.
- Reprocessing: Gypsum from plasterboard wastes was recovered and then supplied back to the manufacturing process.
- Reincorporation: The recycled gypsum was used in the process to manufacture new gypsum products.

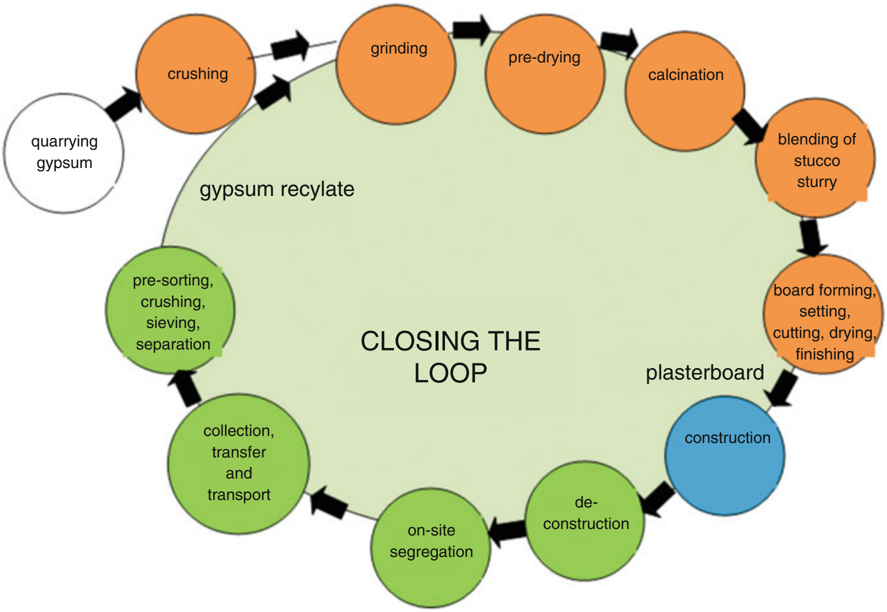


Fig. 2.4 Closing the loop for gypsum from C&D wastes

3.1.2 How Can ISWM Be Applied for a CE Around Gypsum-Based C&D Waste?

An ISWM system for CE around gypsum-based C&D waste begins most importantly with effective dismantling and sorting practices followed by other ISWM functional elements: collection, transfer and transport, and recycling processes.

- On-site segregation: Rather than demolishing construction infrastructure, appropriate techniques and tools are used to dismantle the plasterboard and blocks to minimize the damage to these materials. The gypsum wastes are separated from the other residual C&D waste stream to reduce contamination. The different types of gypsum-based wastes are further sorted (i.e., plaster board, blocks).
- Storage: It is imperative to minimize contamination of gypsum wastes. Thus, containers of specific sizes and quantity are allocated for each type of gypsum-based waste. Closed gypsum steel containers (30 m^3 and 40 m^3 capacity) protect gypsum waste from moisture and wet weather.
- Collection, transfer and transport: Economic and environmental benefits can be achieved by reducing vehicle movement and distances to transport the wastes to a transfer station and/or to a recycling facility.
- Recycling processes: Pre-cleaning and pre-sorting is applied to the wastes prior to the recycling processes. Moisture content is also one of the factors to be considered during recycling, and so the gypsum-based waste is stored with a dryer fraction. The gypsum-based waste undergoes crushing, electromagnetic separation, air separation, and sieving to produce the gypsum recyclate.
- Plasterboard manufacturing: Recycled gypsum is re-introduced during the grinding process and is fed together with the natural gypsum feedstock. Free moisture is removed during the pre-drying process. The feedstock undergoes calcination, which is described as the thermal processing of gypsum to change the hydration state of its dihydrate content by partially or completely removing its chemically bound (or crystal) water in order to produce hemihydrate or anhydrite, respectively. In the manufacture of plasterboards, beta process calcination is used to produce an intermediate product called stucco. The stucco is mixed with water and other dry and liquid additives to produce the slurry for the board's plaster. Board is produced at the forming station, followed by setting and cutting, drying and finishing processes.

3.2 Rare Earth Elements from Phosphorescent Powders in Fluorescent Lamps (FLs)

Linear fluorescent lamps (LFLs) have been in the market for the longest time followed by compact fluorescent lamps (CFLs) and we are now witnessing a transition from fluorescent lights (FLs) to light emitting diodes (LEDs). FLs are considered a concern in municipal solid waste management as they are household hazardous waste which can enter the municipal solid waste (MSW) stream. These FLs contain mercury as vapour inside the glass tubing. Mercury can be released to the environment and bioaccumulate, and it can affect human health causing damage to the nervous system, immune system, reproductive system, motor system, renal system and cardiovascular system. According to the US EPA, a standard FL contains 8–14 mg of mercury, whereas low-mercury bulbs contain 3.5–4 mg of mercury. Data in 2003 reported 620 million FLs disposed in US, which corresponds to a release of approximately 2–4 tons of mercury into their environment (Aucott et al. 2003). In China, waste FLs generated from domestic use alone is predicted to rise to around six billion wastes, or around 937,400 tonnes of waste according to Tan and Li (2014).

Aside from mercury, FLs also contain phosphor powders that are used for their luminescent properties and for producing white light (Machacek et al. 2015). The phosphor powders of FLs contain rare earth elements (REE) such as europium (Eu), terbium (Tb) and yttrium (Y). Thus in the context of resource management, the recovery and recycling of REE from the phosphor powders in FLs presents an option to address resource scarcity of REEs (e.g., global market for REE is increasing by 6% annually) (Solvay 2014). The average composition of FLs, according to the Solvay Loop report is: 88% glass, 5% metals, 4% plastics, 3% powders, and 0.005% mercury. The average composition of the phosphor powders is: 45% halophosphate, 20% glass powder, 20% rare earths, 12% alumina, and 5% others (Solvay 2014). Like other metals, REEs (unlike organic chemicals) are not created or destroyed by biological or chemical processes (although these processes can transform metals from one species, or convert them between inorganic and organic forms), thus in theory metals are eternally recyclable (Reck and Graedel 2012; Schüler et al. 2011; USEPA).

3.2.1 What Model Is Used for This Waste?

Solvay-Rhodia (‘Solvay’) had undertaken a project with EU funding called Solvay “Loop” project which aimed to recycle waste lamp phosphor powders, and to recover REEs. To achieve CE around the recycling of REEs from phosphor powders in waste FLs, Solvay implemented a cradle-to-cradle (C2C) approach, integrating the recycling processes into their existing network (Fig. 2.5). The project focused on the feasibility of using the company’s existing facilities to carry out recycling processes (Solvay 2014).

- Post-consumer waste processing: Solvay already accepts phosphor powders. Thus external recyclers carry the burden of sorting and processing the lamps to produce phosphor powders and a fraction of residual glass.
- Upstream processes (Saint-Fons Chimie plant): Solvay used its own industrial processing facility to separate mercury, glass and other components from the phosphor powders.

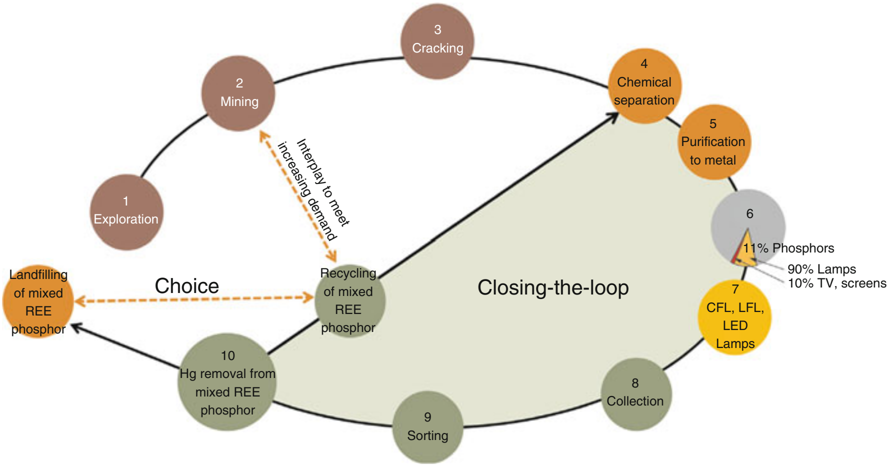


Fig. 2.5 Closing the loop for REEs from phosphor powders in FLs (Reproduced with permission from Machacek et al. 2015)

- Downstream processes (La Rochelle plant): Solvay transported the packaged phosphor powders off-site to one of its other industrial facilities. The processed phosphor powders are purified to recover REEs. The REEs are then reformulated as a supply to manufacture new phosphors.

3.2.2 How Can ISWM Be Applied for CE Around REES from Phosphor Powders in FLs?

To fully achieve CE around the recycling of REEs from the phosphor powders in FLs, the existing network would rely on ISWM for existing separation and purification plants to accept waste phosphor powders. It begins with efficient collection of waste FLs from the consumers. This enables a substantial quantity of waste lamps that can generate secondary resources for REEs. Another important factor to be considered in the post-consumer stage is the dismantling of FLs into different parts; that would enable extraction of maximum value from phosphors.

- Collection: An efficient collection system should enable the consumers to bring the waste FLs, and/or the retailers and manufacturers to accept waste FLs. Examples of collection systems include buy-back programmes and drop-off locations. The wastes are transported to the recyclers of lamps (US EPA 2012).
- Materials recovery: The waste FLs are sorted, dismantled and pre-processed to separate the high-value components from other components such as glass, plastics and metals. Dismantling and pre-processing of the FLs include manual

disassembly, mechanical separation, shredding, screening and demercurization to produce phosphor powders (Solvay 2014; USEPA 2012).

- Recycling processes: Phosphor powders are treated with chemicals in a suspension tank, separated and dried to produce treated powders. The powders then undergo pyrometallurgical thermal treatment, then they are reslurried, filtered, washed and treated with nitric acid. Different REEs are extracted using solvent-extraction processes. Purification of REEs can be done using precipitation, filtration and calcination to produce REE phosphor precursors (Solvay 2014; Machacek et al. 2015).

3.3 Metals from Electronic Wastes (E-Wastes)

Electronic wastes or e-wastes are defined as ‘electrically powered appliances that no longer satisfy the current owner for its original purpose’ (Singh et al. 2012). The 2006 data estimation by UNEP shows that 20–50 million tons/year of e-wastes is generated globally. MSW contains 1–3% of e-wastes. Global issues regarding the management of e-wastes include (1) increasing volume of obsolescent electronics, (2) increasing rate of generation, (3) decreasing life span of the products, (4) low recycling rate, (5) increasing consumer demand, and (5) illegal transboundary movement of e-wastes from developed to developing countries (Sthiannopkao and Wong 2013; Sepúlveda et al. 2010). Studies conducted in Europe also reported that the quantity of e-wastes is increasing by 3–5% per year (Bhuie et al. 2004). Interestingly, the fastest growing category is cell or mobile phones. In the context of waste management, e-wastes are significant because of their toxic and hazardous substances such as metals, polychlorinated biphenyls (PCBs), brominated fire retardants (BFRs) and plastics, and their impacts. On the other hand, for resource recovery, e-wastes also contain recoverable materials such as plastics, heavy metals, precious metals and rare earth elements. Among the precious metals (PMs) that can be recovered are Au, Ag, Pd, as well as the Base Metals (BMs) like Cu, Pb and Zn. For example, the amount of gold that can be potentially extracted from 1 ton of PCs is reported to be more than that of 17 tons of gold ore. Or for mobile phones, an average tonne of used mobile phones represents a potential of 128 kg of copper, 0.347 kg of gold, 0.15 kg of palladium, 3.63 kg of silver, 15 kg of nickel, 6 kg of lead, 1 kg of antimony, and 10 kg of tin as well as other metals (Navazo et al. 2014). Current e-waste management problems focus on the international trade of e-wastes between developed and developing countries practiced nowadays because valuable materials and substances (copper), rare (yttrium, cerium, lanthanum, europium, terbium, dysprosium, lutetium, gadolinium) and precious (gold, silver, platinum) metals can be sourced from these e-wastes. “Urban mining” (Habuer and Moriguchi 2014) has become another driving force for this trade. E-wastes become secondary sources of these valuable materials (Lundgren 2012) from which the “recyclers” can gain financial benefits.

3.3.1 What Model Can Be Used for E-Waste Management?

Wang et al. (2012) and Manhart (2011) introduced a novel philosophy to address e-waste management issues called the Best-of-Two-Worlds (Bo2W). This concept came from the StEP Initiative (Solving the E-waste Problem) and the United Nations University. It uses the technological and logistic strengths of both developed and developing countries to form a complete recycling chain in the best geographically distributed treatment options in the international or regional arena. Pilot projects were implemented in China and India. Recent Bo2W projects were implemented in Egypt and Ghana. A project by Oeko-Institut in 2012–2015 studied the implementation of Bo2W in two cases: dismantling in Egypt/Ghana and state-of-the-art treatment in European refining plants (Buchert et al. 2016).

- Local pre-processing: Developing countries can still use manual dismantling of the locally-generated e-wastes with low technical requirements. Labour costs in developing countries are also lesser than in industrialized countries (Wang et al. 2012).
- Regional processing: More advanced and automated materials recovery or processing facility can be made available at a regional level.
- End-processing: Industrialized countries offer state-of-the-art and capital-intensive technologies for the overall detoxification and recovery of the valuable materials such as metals (Wang et al. 2012).

3.3.2 How Can ISWM Be Applied to the Bo2W Concept?

The Bo2W approach requires implementation of various elements of ISWM at various geographic locations from a local scale to the global scale.

- Collection: Theoretically, in an efficient collection system, even in developing countries there is need for circularity in e-waste management. Various collection methods can be undertaken by multiple stakeholders: companies, small and medium enterprises (SMEs), public sector, non-government organizations, and the informal sector. Better options can be implemented by retailers and manufacturers using take-back policies or drop-off points. The collection system must ensure that maximum volumes of e-wastes can be brought for recycling.
- Materials recovery: After collection, e-wastes are sorted where useable parts may be used for repair, refurbishment. The wastes are also sorted according to the different types.
- Pre-processing: E-wastes are manually dismantled at local facilities. Automated pre-processing may also be applied to e-waste components using mechanical separation technologies such as screening, magnetic separation, eddy current separation and density separation.
- Recycling processes: E-waste components that require removal of toxic substances are exported to recycling facilities in developed countries. Likewise, the extraction and purification of metals from the pre-processed e-waste components

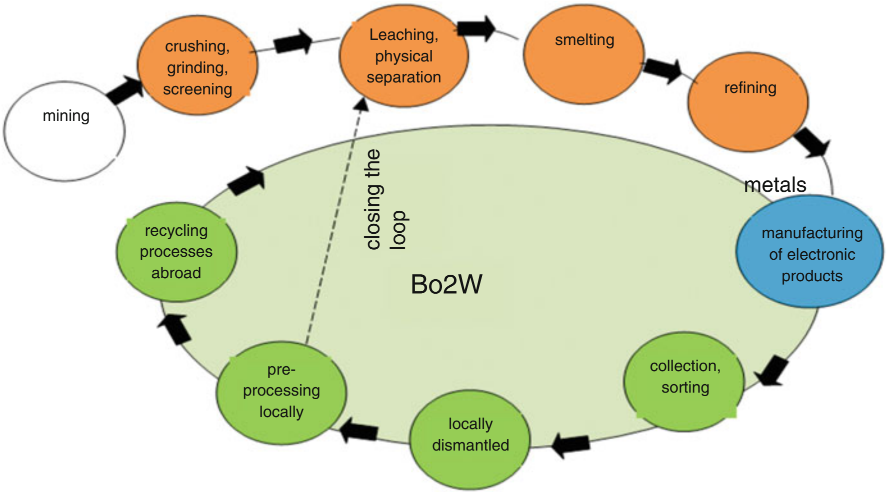


Fig. 2.6 Bo2W and closing the loop model of metals from e-wastes

are done in industrialized countries using various metallurgical processes. Also, recycling processes are based on traditional hydrometallurgical methods of metal extraction from primary ores (Khaliq et al. 2014).

3.3.3 Will a Closed Loop Be Possible for Metals from E-Wastes?

In Australia, the objective of a project called Wealth from Waste Cluster (a three-year project from 2009 to 2012) is to determine the feasibility of metal recovery from discarded products, using expertise in mining and metal extraction processes. Using the conceptual framework for metal flows presented by Golev and Corder (2014) as a basis, the Bo2W model can be improved to integrate the closed loop model as shown in Fig. 2.6. This closed loop is proposed to recycle and recover metals from end-of-life products using processes from the mining and metals manufacturing industry.

4 Summary

From the different examples discussed in this chapter, the following ISWM functional elements contribute to successful implementation of a CE (excluding disposal, which is considered as the last option in the waste management hierarchy):

- Generation of solid wastes: Programmes and strategies to reduce the quantity of solid wastes generated and improve its quality focus on the implementation of

3Rs (reduce-reuse-recycle) such as designing for the environment (green design), material substitution, online retailing. The technical materials could also focus on using resources that can be infinitely recycled.

- On-site segregation and storage: Separation of solid wastes at the source to optimize the quantity and quality of valuable secondary resources. Care, effort, and sometimes skills are required to minimize contamination and deterioration of the useful fractions of solid wastes.
- Collection: Efficient collection systems need to address several factors such as availability, and convenience in order to maximize the capture rate of solid wastes. Current practices include take-back programmes, and drop-off centres. In developing countries, integration of the informal sector optimizes the collection system. Programmes and strategies for efficient collection systems rely increasingly on social and government factors (i.e., public awareness, laws and regulations). In CE, on-site segregation and collection are considered the critical functional elements because they affect the quality and quantity of the secondary resources obtained from the wastes.
- Transfer and transport: Routes between collection centres and materials treatment facilities can be optimized to minimize the distance travelled between facilities. Warehouses or transfer stations may be located in regions where solid wastes generated or purchased are high, or near the recycling facilities. An emerging strategy is to combine the transfer of wastes and recycling processes in a mobile unit.
- Treatment, processing and recovery: In CE, extraction of secondary resources involves pre-processing and end-processing stages. Recycling processes may be complex and extensive, and may require state-of-the-art technologies. When secondary materials are mixed with primary materials during remanufacturing, it may require process and equipment modifications.

References

Aucott, Michael, Michael McLinden and Michael Winka, 2003. Release of mercury from broken fluorescent bulbs. *Journal of the Air & Waste Management Association*, **53**(**2**), 143.

Bermejo, Roberto, 2014. Handbook for a Sustainable Economy. Springer.

Bhuie, A.K., Ogunseitan, O.A., Saphores, J.-D.M. and Shapiro, A.A., 2004. Environmental and economic trade-offs in consumer electronic products recycling: A case study of cell phones and computers. IEEE International Symposium on Electronics and the Environment, 2004. Conference Record.

Bollinger, L.A., 2010. Growing cradle-to-cradle metal flow systems: An application of agent-based modelling and system dynamics to the study of global flows of metals in mobile phones. A thesis paper. Delft University of Technology, Leiden University.

Buchert M, Manhart A, Mehlhart G, Degreif S, Bleher D, Schleicher T, Meskers C, Picard M, Weber F, Walgenbach S, Kummer T, Blank R, Allam H, Meinel J, Ahiayibor V (2016) Transition to sound recycling of e-waste and car waste in developing countries - Lessons learned from implementing the Best-of-two-Worlds concept in Ghana amd Egypt. A synthesis report of the project Global Circular Economy of Strategic Metals - Best-of-two-Worlds approach (Bo2W). Oko-Institute. V., Darmstadt. http://www.resourcefever.org/publications/reports/Bo2W_Synthesis_report_20160323_en.pdf.

CIRAIG International Reference Centre for the Life Cycle of Products, Processes and Services. 2015. Circular Economy: A critical review of concepts. http://www.ciraig.org/pdf/CIRAIG_Circular_Economy_Literature_Review_Oct2015.pdf

Ellen MacArthur Foundation, 2012, 2013. Towards the Circular Economy: Opportunities for the Consumer Goods Sector. Vol. 1&2.

Ellen MacArthur Foundation, 2016. Circular Economy – UK, Europe, Asia, South America & USA. Ellen MacArthur Foundation. http://www.ellenmacarthurfoundation.org/circular-economy

Eurostat, 2011. Waste Statistics. *In:* Archive: Waste Statistics – Statistics Explained. http://ec.europa.eu/eurostat/statistics-explained/index.php/Archive:Waste_statistics

Florin, N., Madden, B., Sharpe, S., Benn, S., Agarwal, R., Perey, R. and Giurco, D., 2015. Shifting Business Models for a Circular Economy: Metals Management for Multi-Product-Use Cycles. UTS, Sydney.

GEO5 (Global Environmental Outlook 5), 2012. Global Environmental Outlook 5 – Environment for the future we want. ISBN: 978-92-807-3177-4. United Nations Environment Program, Nairobi.

Golev, A. and Corder, G.D., 2014. Global systems for industrial ecology and recycling of metals in Australia: Research report. Prepared for Wealth from Waste Cluster, by the Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland. Brisbane, Australia - ONLINE.

GtoG, 2015. Gypsum to Gypsum: From Production to Recycling, a Circular Economy for the European Gypsum Industry with the Demolition and Recycling Industry. LIFE11 ENV/BE/001039. <http://gypsumtogypsum.org/>

Habuer, Nakatani J. and Moriguchi, Y., 2014. Time-Series Product and Substance Flow Analyses of End-Of-Life Electrical and Electronic Equipment in China. *Waste Manag*., **34(2)**, 489–497. Elsevier Ltd.

Hagelüken, C., (2006). Improving metal returns and eco-efficiency in electronic recycling—a holistic approach for interface optimisation between pre-processing and integrated metals smelting and refining. In: Proceedings of the 2006 IEEE international symposium on electronics and the environment, San Francisco, California, 8–11 May 2006. IEEE, pp 218–223.

Hoornweg, Daniel and Perinaz Bhada-Tata, 2012. What a Waste: A Global Review of Solid Waste Management. World Bank. https://openknowledge.worldbank.org/handle/10986/17388.

Hosoda, Eiji, 2007. International aspects of recycling of electrical and electronic equipment: Material circulation in the East Asian region. *Journal of Material Cycles and Waste Management*, **9(2)**, 140–150.

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor and H.L. Miller (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Khaliq, Abdul, Muhammad Akbar Rhamdhani, Geoffrey Brooks and Syed Masood, 2014. Metal extraction processes for electronic waste and existing industrial routes: A review and Australian perspective. Vol. 3. Basel: MDPI AG.

Lundgren, K., 2012. The Global Impact of E-Waste: Addressing the Challenge. International Labour Office, Programme on Safety and Health at Work and the Environment (Safe Work), Sectoral Activities Department (SECTOR). ILO, Geneva.

Machacek, Erika, Jessika Luth Richter, Komal Habib and Polina Klossek, 2015. Recycling of rare earths from fluorescent lamps: Value analysis of closing-the-loop under demand and supply uncertainties. *Resources, Conservation and Recycling*, **104**, 76–93. Doi: 10.1016/j.resconrec.2015.09.005.

Manhart, Andreas, 2011. International cooperation for metal recycling from waste electrical and electronic equipment. *Journal of Industrial Ecology*, **15(1)**, 13–30.

Navazo, V., Manuel, J., Villalba Méndez, G. and Talens Peiró, L., 2014. Material flow analysis and energy requirements of mobile phone material recovery processes. *The International Journal of Life Cycle Assessment*, **19(3)**, 567–579.

Quanyin Tan and Jinhui Li, 2014. A study of waste fluorescent lamp generation in mainland China. *Journal of Cleaner Production*, **81**, 227–233. http://dx.doi.org/10.1016/j.jclepro.2014.06.048.

Reck, B.K. and Graedel, T.E., 2012. Challenges in Metal Recycling. *Science*, **337(6095)**, 690–695. doi:10.1126/science.1217501.

Schüler, D., Buchert, M., Liu, R., Dittrich, S. and Merz, C., 2011. *Study on rare earths and their recycling*. Öko-Institut e.V., Darmstadt.

Sepúlveda, A. et al., 2010. A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipment during recycling: Examples from China and India. *Environmental Impact Assessment Review*, **30(1)**, 28–41.

Suthipong Sthiannopkao, Ming Hung Wong, 2013. Handling e-waste in developed and developing countries: Initiatives, practices, and consequences. Science of The Total Environment, Volumes 463–464, https://doi.org/10.1016/j.scitotenv.2012.06.088.

Singh, R.K., Murty, H.R., Gupta, S.K. and Dikshit, A.K., 2012. An overview of sustainability assessment methodologies. *Ecological Indicators*, **9**(**2**), 281–299.

Solvay, 2014. Loop Life Project, https://www.solvay.com/en/innovation/european-life-projects/loop-life-project-objectives.html, last accessed on 02.03.2016.

U.S. Environmental Protection Agency, 2012. Rare Earth Elements: A review of production, processing, recycling, and associated environmental issues. EPA 2012, 600/R-12/572.

Van de Klundert, A. and Anshutz, J., 1999. Integrated Sustainable Waste Management: The selection of appropriate technologies and the design of sustainable systems is not (only). A technical issue Paper prepared for the CEDARE/IETC Inter-Regional Workshop on Technologies for Sustainable Waste Management, held 13-15 July 1999 in Alexandria, Egypt.

van Dijk, S., Tenpierik, M. and van den Dobbelsteen, A., 2014. Continuing the building's cycles: A literature review and analysis of current systems theories in comparison with the theory of Cradle-to-Cradle. *Resources, Conservation and Recycling*, **82**, 21–34.

Wang, Feng, Jaco Huisman, Christina E. M. Meskers, Mathias Schluep, Ab Stevels, and Christian Hagelüken, 2012. The best-of-2-worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. *Waste management*, **32**(**11**): 2134.

Wilson, D., Velis, C. and Rodic, L., 2013. Integrated sustainable waste management in developing countries. *Waste and Resource Management*, **166(2)**, 52–68.

Chapter 3
Institutional Waste Management

Sanjeev Kumar, Anjani Devi Chintagunta, Knawang Chhunji Sherpa, and Rintu Banerjee

1 Introduction

Indian society was regarded as a traditional society until the first quarter of the twentieth century and modernisation emerged thereafter due to change in the social values that are attributed to creation of new social structure and social institutions. Though modernization and advancement in science and technology improves the living standards of the people in the society, it also results in greater exploitation of natural resources and pollution of the environment. In a decade, India has added nearly 20,000 colleges, i.e., the number of colleges increased from 12,806 in 2000–2001 to 33,023 in 2010–2011 which translated into growth of more than 150%. Numbers of degree colleges have doubled from 256 to 564 and IITs (Indian Institute of Technology) have increased from 7 to 23 in a span of 20 years. As a consequence of the increase in educational institutions and other government sectors, enormous amount of waste is being generated with a negative impact on the environment.

Institutional waste is waste generated from schools, universities, hospitals, government and private offices, prisons, religious and research institutes. Improper handling and disposal of this waste can pose a serious threat to human health and environment. India is often lacking in waste management due to inadequate facilities and improper disposal of waste. Therefore, in order to educate people about waste management, learning and practice should start from the education system since they are the pillars of our society. As per the General Law for Waste Prevention and Integrated Management (SEMARNAT 2003) waste generators are directed to reduce waste generation and to valorize waste in an integrated manner.

S. Kumar • A.D. Chintagunta • K.C. Sherpa • R. Banerjee (✉)
Bioethanol Lab, P.K. Sinha Centre for Bioenergy, Indian Institute of Technology Kharagpur, Kharagpur 721302, India
e-mail: rb@agfe.iitkgp.ernet.in

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_3

The E-waste (Management and Handling) Rules, 2015, the Hazardous Wastes (Management, Handling and Transboundary Movement) Rules, 2008 and the Plastic Waste (Management and Handling) Rules, 2011 are framed for proper treatment of electronic, hazardous and plastic wastes, respectively. With stringent environmental laws being enforced in recent years, it is necessary to frame some goals to manage waste globally. The goals include safe and secure waste collection services, restrictions on uncontrolled dumping and open burning, minimization of waste generation by reduce, reuse, recycle and recovery strategies for sustainable and eco-friendly waste management practices.

1.1 Classification of Institutional Waste

As institutional waste covers mainly teaching and research activities, the main contaminants or the waste which are generated in such places are different from industrial, or residential or commercial waste, etc. Detailed classification of institutional waste and its treatment is described below and shown in Fig. 3.1.

1.1.1 Solid Waste

Different types of organic, inorganic, hazardous and electronic wastes are generated by institutions regularly. Institutional kitchens or canteens are the main source of organic waste while paper waste and electronic wastes come from administrative and other areas. Since the institution campuses are surrounded by roadside trees and gardens, a lot of plant wastes are also generated during proper maintenance of gardens. Institutional solid wastes can be classified as shown in Table 3.1 (Smyth et al. 2010).

1.1.2 Liquid Wastes

Huge quantity of waste water is also generated by institutions in the form of sanitary and cleaning/washing wastewater. Generally, liquid chemicals or reagents like acids, alkalis, etc. discharged from educational, medical and research institutions are directly channelled into the drains. Along with human activities, environment also plays a role in the addition of wastewater like run-off water during rain, excess water flowing from field and garden. Institutional wastewater generally contains chemicals like noxious organic compounds, heavy metals, phenols, nitrogen and phosphorus. In liquid waste, total organic content and biodegradable organic content are characterized by measuring chemical oxygen demand (COD) and biological oxygen demand (BOD), respectively.

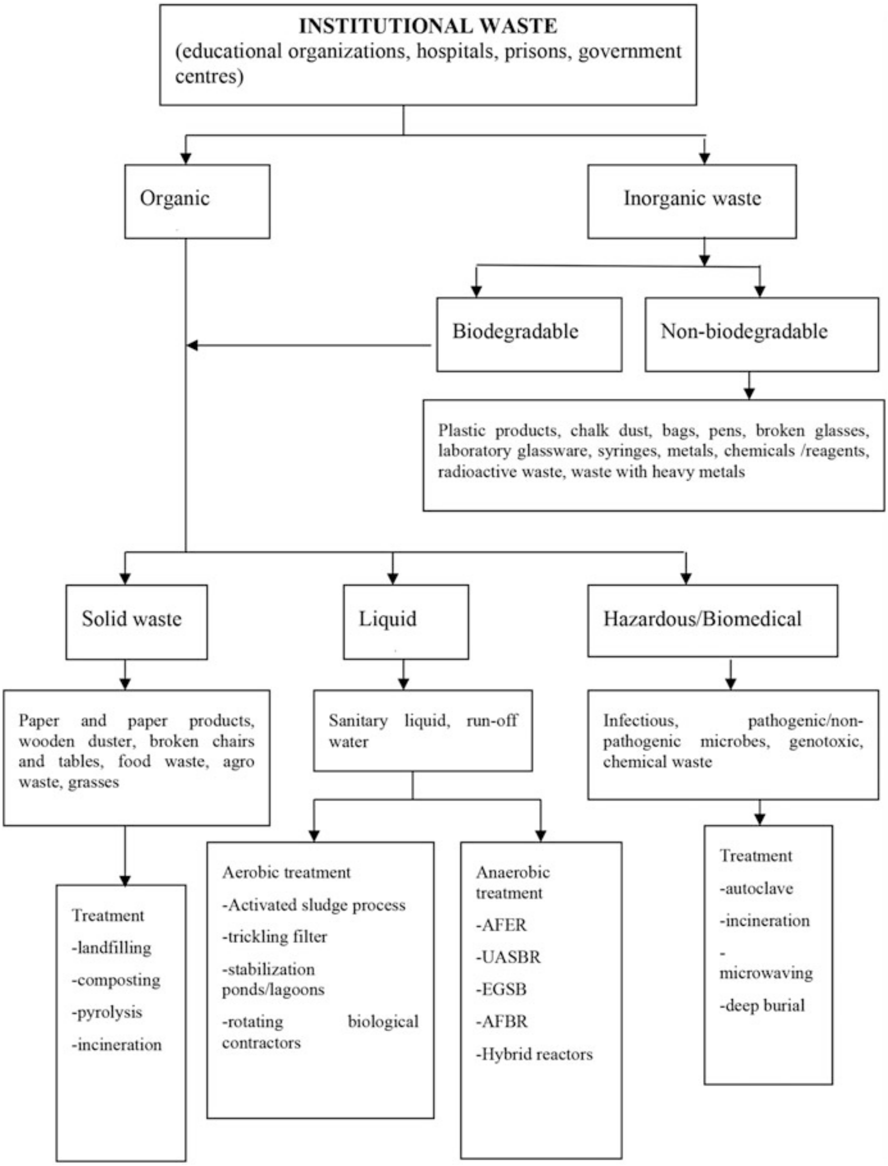


Fig. 3.1 Detailed classification and treatment of institutional waste

1.1.3 Mixed Waste

Hazardous waste poses a substantial danger to humans, animals and the environment as it may not be readily degradable and can persist for prolonged durations of time in the environment. These wastes can be solid, liquid or gaseous and may be

Table 3.1 Classification of institutional solid waste

Category	Description
Paper and paper products	Non-confidential paper, one side printed paper, magazines, catalogues, coloured paper, envelopes, etc.
Corrugated cardboard	Old corrugated cardboard, newspapers, cereal and tissue boxes, packing boxes, etc.
Plastics products	Plastic beverage containers, plastic bags and packaging, pens, plastic tray, plastic utensils, cartons, mugs, etc.
Glass	Glass beverage containers, window glass and broken glassware from laboratories, etc.
Metal	Iron, stainless steel, aluminium foil, copper wire, etc.
Organic matter	Raw fruits, vegetables, excess cooked food, leftover food, etc.
Textiles	Clothing, cleaning rags, etc.
Hazardous waste	Batteries, paint cans, biological samples, toxic chemicals, etc.
E-waste	Electronics and electronics packaging, discarded computers, printers, mobiles, cartridges, electrical appliances, etc.
Miscellaneous	Chalk powder, ink, agro wastes, waste from construction, tiles, ceramics, rubber/tubes, footwear, etc.

containerized or open. Biomedical waste is one of the major categories of hazardous wastes which are generated during diagnosis, immunization, treatment of human being or animals and other related research and treatment activities. Biological laboratories (microbiological, pathological, veterinary, etc.) are also producing a considerable amount of hazardous waste in the form of chemicals, radioactive elements and microorganisms. The World Health Organisation (WHO) has classified biomedical waste into general, pathological, radioactive, chemical, infectious, sharp, pharmaceutical and pressurized container waste. In India, hazardous waste generated from hospitals ranges from 15% to 35% depending on the total amount of waste produced (Chitnis et al. 2005). Proper disposal of waste is a crucial task without which infectious pathogens, mutagens and other cancerous agents may spread in the environment and pose severe health hazards.

1.2 Major Problems Associated with Institutional Waste

Improper disposal of institutional waste not only spreads foul smell in the environment but is also responsible for various air, water and food-borne diseases. According to World Health Organisation (WHO), more than 50,000 people die from infectious diseases every day. One of the major reasons for the spread of infectious diseases is inappropriate waste management. For example, infectious diseases like pneumonia, tuberculosis, diarrhoea, whooping cough etc. are a consequence of improper waste management (Marinkovic et al. 2005). Exposure to harmful gases emitted from open burning can cause cancer and respiratory diseases

(Da Silva et al. 2005). When animals ingest waste containing plastic, it can obstruct the digestive systems of animals and also cause other severe problems. Harmful chemicals like furans and dioxins can also cause serious health problems in animals and birds. Some heavy metals have adverse impacts on the reproduction of animals (Code and Christen 1999). Waste management practices have been initiated in urban areas, but have not spread to semi-urban and rural areas.

Special emphasis should be given to sources of waste generation as the characteristics and composition of the waste vary depending on their source. While proposing a strategy on waste management, source of waste generation, characteristics of the waste and conditions of the market for recyclables should be taken into consideration. Along with waste collection and transportation, other schemes including reduction, segregation and valorization of wastes that could help the generators to improve their waste management practices should be executed.

2 Biotechnological Approaches for Waste Treatment

Disposal of institutional waste on land is the most common practice implemented in developed as well as in developing countries as it is a cheap disposal method. In developing countries this takes the form of open dumping while in developed countries this waste is generally disposed in appropriately engineered landfills. Selection of an appropriate treatment method before disposal depends on the cost and prevailing local circumstances. Biological treatment of waste is an alternative method to reduce landfill requirement, emission of greenhouse gases from landfills and leachate contamination. These processes can be broadly classified as aerobic and anaerobic process. Process selection depends on the type of waste, percentage of organic and inorganic content in the waste, required degree of treatment and cost of the process. Aerobic processes are preferred when the liquid wastes have low organic content in the range of 100–3000 mg/L, low energy requirements for mixing the oxygen and low sludge production. Anaerobic processes are cost-effective for treating solid organic waste and liquid waste with BOD_5 above 3000 mg/L because it requires less energy to maintain the process and also results in value added products like biogas. Another viable method of waste treatment is anaerobic-aerobic sequencing biological wastewater treatment system (AASB) where 50-55% of organic content is reduced by anaerobic treatment followed by aerobic treatment for further minimisation. AASB produces high quality effluents and biogas by utilising 68% less energy than that of the traditional methods (Fricke et al. 2005). The various reactor systems employed for wastewater treatment include batch, plug flow, continuous flow stirred tank reactor (CSTR), packed bed and fluidized bed reactors. These reactors differ from each other in their shape and dimensions, mode of material flow, degree of mixing, packing material and their characteristics, etc.

2.1 Landfilling

An engineered landfill is a specified area of land into which waste is deposited to avoid any contact between the waste and the surrounding environment, especially with the groundwater. Landfills can be classified as sanitary landfills for municipal solid waste and secure landfills for hazardous waste. Water infiltrates into the landfill waste during the rainy season, is released during compaction and degradation of waste and results in the formation of leachate containing hundreds of toxic substances like cadmium, lead, mercury, chromium, dioxins, toluene, organophosphates and polychlorinated biphenyls (PCBs). As landfill leachate is responsible for contaminating surface as well as groundwater ecosystems, precautionary measures are necessary for its prevention. The decomposition of waste in the landfill area leads to the generation of gases, which are a mixture of methane, carbon dioxide and carcinogenic volatile organic compounds, such as benzene, toluene, xylenes, carbon tetrachloride, etc. Exposure to these chemicals can result in several health hazards such as cancer, and chronic obstructive pulmonary diseases.

2.2 Composting

Composting is a process in which organic matter is decomposed under controlled conditions through biological processes, resulting in the formation of nutrient-rich humus. During this process, vegetable residue, agro waste, leftover food waste, soil and water are mixed with microorganisms such as mesophilic and thermophilic bacteria and fungi to form humus, which enhances soil fertility and increase crop productivity. Centralized composting plants for treating unsegregated (mixed) waste have proved to be uneconomical due to the presence of large amounts of inorganic materials which lead to the formation of poor quality end products. The presence of non-biodegradable plastics in the waste stream is problematic as the material does not get recycled. In order to practice best waste management strategies, the prime pre-requisite for composting is to segregate the mixed waste into organic and inorganic waste. The process will be more cost-effective if segregation occurs at the waste generation site, from where the biodegradable waste can be sent for composting and the other material for recycling.

Microorganisms and earthworms jointly transform organic matter into nutrient-rich biofertilizer making composting a viable alternative for the solid waste management (Ismail 2000). Microbes are accountable for the biochemical degradation of organic matter, whereas earthworms are involved in conditioning the substrate and altering its biological activity (Aira et al. 2007). Nevertheless, the quality and processing time of the end-product differ according to the composition of the initial organic material (Singh et al. 2010). Hence, vermicomposting has been considered to be a rapid, viable and cost-effective technique for efficient solid organic waste management.

2.3 Aerobic Treatment of Wastewater or Leachate

In aerobic treatment, organic and inorganic materials are oxidized by aerobic microorganisms such as fungi, bacteria, algae, protozoa and rotifers. Highly engineered bioreactors are required for maintaining optimum conditions for microbes to oxidize the waste rapidly. Aerobic processes have high efficiency (90-95%) in terms of contaminant removal from the waste and reduce BOD to acceptable levels. Common methods employed for solid waste treatment are landfilling and composting whereas trickling filter, activated sludge process, stabilization ponds/lagoons are used for liquid waste treatment.

2.3.1 Activated Sludge Process (ASP)

While treating waste, primary treatment is not sufficient to remove the dissolved wastes and colloids due to which a secondary treatment process is required. Sewage is characterized by a low COD (chemical oxygen demand) to BOD_5 (five-day biological oxygen demand) ratio and is subjected to secondary treatment which is biological in nature. Activated sludge process is a biological treatment process and is widely used since it is efficient, simple to operate and cost-effective in nature.

ASP mainly consists of four main components: (1) an aeration tank which consists of suspended microorganisms and dissolved oxygen that help in the degradation of dissolved organic matter and colloids. The organic matter is stabilized by the action of bacteria under aerobic conditions for their source of energy by catabolism process and transformation of organic matter into cellular mass through anabolism. (2) Clarifier or settling tank where the suspension of microbes and waste water called "mixed liquor" flows into the tank. The solids or the flocculated biomass settles to the bottom by gravity and the clarified effluent flows out of the system (3) a return sludge pump helps in maintaining a high microbial concentration by recycling a major portion of the settled sludge back to the bioreactor. This in turn helps in increasing nutrient removal and controls the duration of microbes that remain in the bioreactor which is also called as mean cell retention time (MCRT) or the sludge age (SRT) (4) sludge wastage line which is situated at the bottom of the clarifier is used to withdraw the excess sludge in order to maintain the biomass concentration and SRT. In modern ASPs, integrated degradation processes like ozonation, chemical oxidation, and ultraviolet radiation are being used to minimize sludge production.

2.3.2 Trickling Filter

Trickling filters consist of a fixed film that covers the surface of the bed and the wastewater trickles over this media surface so as to remove the BOD and suspended solids. In this treatment, aerobic bacteria on the biofilm come in contact with organic matter and help in the oxidation process. The biofilm mainly consists of bacteria but growth of other organisms like fungi, algae, protozoa, worms, snails and insect larvae also occurs. With time, the biofilm thickness increases due to which anaerobic conditions are created in the deeper layers of the biofilm leading to sloughing and this biomass flows out along with the treated water into the secondary sedimentation tank. In order to improve the efficiency of trickling filters, many methods are developed such as two-stage hybrid system wherein the system consisted of a vertical flow trickling filter (VFTF) and a horizontal flow multi-soil-layering (HMSL) bioreactor which are able to remove more than 90% organic matter, nitrogen and phosphorus (Zhang et al. 2015).

2.3.3 Stabilization Pond/Lagoon

This is the most common and simplest form of biological treatment process that serves many basic purposes like storage of wastewater, settling and removal of suspended solids, equalization, aeration, treatment and evaporation. Easy handling and treatment of wastewater makes it a low cost process and a preferred technology. Stabilization pond receives partially treated sewage. Basically it is a pond that is dug at least 1 to 1.8 m into the ground with shallow depth so as to prevent the growth of aquatic weeds. The confinement period of the sewage in the pond is 2 to 6 weeks depending on environmental factors like sunlight and temperature. Ponds placed in succession show better efficiency (more than 90% BOD removal) in the treatment of waste.

2.3.4 Rotating Biological Contactors (RBC)

Rotating Biological Contactors (RBC) takes its inspiration from trickling filter wherein a series of rotating plastic media coated with a layer of biofilm are placed. The biofilm on the media undergoes oxidation and nitrification while reacting aerobically with the wastewater and while reacting anaerobically undergoes denitrification. The plastic media that are typically about 3.5 m in diameter are mounted side-by-side and attached to a horizontal shaft that rotates. Each disc is approximately 40% immersed in wastewater for degradation of organic matter by the microbes growing on the film. Just as in trickling filter, excessive growth of microbes on the media leads to sloughing same case applies in RBC as well. The advantage of RBC over trickling filter is that it is easier to operate under different load conditions.

2.4 Anaerobic Treatment of Wastewater or Leachate

Anaerobic treatment is the prevailing option for a variety of organic wastes with the production of renewable and clean energy by mesophilic and thermophilic anaerobes. High rate modern anaerobic processes retain viable biomass by some modes of bacterial sludge immobilization methods. Entrapment of sludge aggregates in the packing material occurs in downflow or upflow anaerobic fixed-film reactors (AFFR) whereas formation of highly settleable sludge aggregates in combination with gas separation and sludge settling occurs in upflow anaerobic sludge blanket reactor (UASBR) and anaerobic baffled reactor (ABR). On the other hand, bacteria are attached to high density particulate carrier material in anaerobic fluidized bed reactor (AFBR) and anaerobic expanded bed reactor (AEBR).

2.4.1 Anaerobic Fixed-Film Reactor (AFFR)

The AFFR employs a biofilm support structure such as polyvinyl chloride, activated carbon, ceramic rings or hard rock particles for biomass immobilization, and can be operated either in the upflow or downflow mode. The reactor has a simple configuration without need for mechanical mixing and can withstand toxic and high organic shock loads. The reactor is susceptible to clogging caused due to increase in film thickness and high suspended solid content of wastewater or leachate.

2.4.2 Upflow Anaerobic Sludge Blanket Reactor (UASBR)

The most important feature of a UASBR is the formation of granular sludge which is an agglomeration of microbial consortia. The system consists of a gas–solid separator, a feed distribution system, and effluent draw-off facilities. Even at low organic loads, sufficient contact between waste water and sludge is guaranteed; hence, effluent recycle is not necessary. The design of the reactor is cost effective and cell retention time is high due to formation of granular sludge with high particle size. The disadvantage of this system is that it requires seed sludge for faster start up.

2.4.3 Expanded Granular Sludge Bed (EGSB)

The modified form of UASBR is expanded granular sludge bed (EGSB) where a slightly higher superficial liquid velocity can be applied for the accumulation of granular sludge. In EGSB, microorganisms are attached to an inert support made up of sand, gravel or plastics similarly to that of fluidized bed reactor but with slightly bigger particle diameter. EGSB facilitates efficient flow of substrate into the sludge aggregates, thereby providing better contact between them.

2.4.4 Anaerobic Fluidized Bed Reactor (AFBR)

In AFBR, the bacteria is attached to small-sized particles of sand, activated carbon etc. and is kept in fluidized state by the drag forces exerted by the upflowing waste water. The fluidized media facilitates the proper movement of microbial cells, thereby enhancing the contact between micro-organisms and the substrate. The reactor consists of a feed distribution system, a media support structure, media, head space, effluent draw off and recycle facilities. Size and density of the inert media, bed regeneration, and upflow velocity are deciding factors for biofilm thickness. It is possible to operate the reactor at higher loading rates and at lower retention times. The stationary packed bed technology is sufficient to treat easily biodegradable waste water or water in which high COD removal is not required, while the fluidized bed technology is suitable to treat high strength complex waste water with components that are difficult to degrade.

The hybrid reactors are designed by combining the properties of the UASB and fixed film reactors. By employing this reactor, the adhesion of microbes can be greatly improved along with enhanced concentration of activated sludge. Thus, the liquid waste can be managed by selecting an appropriate treatment process according to its nature.

Other sustainable approaches for the utilization of organic waste are generation of energy or other value added products. The organic waste acts as a substrate for biotechnological transformation into biofuels and microbial fuel cells (MFCs). Waste biomass such as wood and waste food is attractive cheap organic raw material for biofuels production (Yan et al. 2011). Ethanol and butanol production from cellulosic biomass is gaining immense importance owing to its availability, reduction of global warming and no adverse environmental impact. Biomethane and biohydrogen are referred to as clean renewable energy sources and produced by anaerobic digestion of waste having high energy content in the range of 50-55 and 120–142 MJ/kg respectively (Sarma et al. 2013). MFCs are the devices which convert chemical energy present in the organic matter to electrical energy using microorganisms such as bacteria as catalysts under anaerobic conditions (Park and Zeikus 2000). MFCs utilise a variety of carbohydrates and complex substrates present in wastewaters and renewable biomass especially organic waste. The construction and analysis of MFCs requires knowledge of scientific as well as engineering fields ranging from microbiology, electrochemistry and environmental engineering. In MFCs, the breakdown of substrate into carbon dioxide and water takes place with simultaneous production of electricity.

2.5 Biomedical Waste Management and Precautionary Measures

Under the Environment Protection Act (EPA) of 1986, Biomedical Waste Management (BWM) Rules 2016 were formulated for biomedical waste management in India. Details regarding the types of biomedical waste, colour coding, categorization and methods of treatment for disposal as per the newly revised BWM Rules 2016 are provided in Appendix B. Laboratory and pathological waste such as microbial wastes, blood samples and blood bags must be pretreated on-site according to the guidelines of WHO or National AIDS Control Organisation and then handed over as biomedical waste.The final disposal of infectious biomedical waste is carried out by incineration with combustion efficiency of 99% with minimum temperature of 850 °C for primary and 1050 °C for secondary chamber. While autoclaving the hazardous waste, temperature and pressure should not be less than 121 °C and 15 psi and should be kept for 1 h. Whereas if the temperature and pressure is 135 °C and 31 psi it should be kept for 45 min and for 30 min if the temperature and pressure is 149 °C and 52 psi respectively which is then followed by discarding of the waste. Dry heat sterilization that operates at 185 °C for a residence period of 150 min with a sterilization period of 90 min can be used to treat the waste sharps present in the biomedical waste. The mild pharmaceutical waste such as cough syrups, vitamins, eye drops, etc. is being incinerated together with the infectious waste. Incineration ashes which have toxic or hazardous constituents higher than the prescribed limits must be disposed according to the Hazardous Waste (Management, Handling and Transboundary Movement) Rules published in 2008. Besides incineration, the burial method can be adopted wherein the biomedical waste is buried in a trench or pit that is approximately two metres deep. The pit is only half-filled with the waste which is followed by layering it with lime till 50 cm from the surface and then filling it with soil. After burial, precaution should be taken so that the site is not accessible to the animals, for which galvanised iron cover or wire mesh can be used. While disinfecting the waste chemically, at least 10% sodium hypochlorite should be used instead of 1% as given in the revised Bio-Medical Waste Management Rules 2016. This is done so since 1% sodium hypochlorite did not demonstrate 4-log reduction efficiency for microbes. According to the study conducted by Chitnis et al. (2002), contaminated sharps such as needles were exposed to 1% hypochlorite solution for disinfection which was then followed by viability counts. Their observation showed that 15–30% needles contaminated with test bacteria *S. aureus* NCTC 6538 and *E. coli* NCTC 10418 demonstrated less than 5-log reduction in viable counts thus proving that 1% hypochlorite disinfection is inadequate for proper treatment.

Healthcare waste management requires special attention and awareness about the diseases associated with poor practices such as exposure to the toxic and infectious agents, etc. WHO has prepared a document “Safe management of wastes from healthcare activities”, addressing the planning issues, regulatory framework, waste minimization and recycling, handling, storage and transportation, treatment and disposal options, and training. WHO in collaboration with other partners is also framing training modules on good practices viz., identification, classification and safe disposal of waste by implementing various strategies in healthcare waste management. Annual report should be made by the committee which should hold a meeting twice in a year and should report on the training of its workers handling the bio-medical waste. They should also ensure that training is provided to the workers at least once a year so as to make them aware of the work they are involved in. Immunization should also be given to the workers against diseases such as Tetanus and Hepatitis B which could get transmitted while handling biomedical waste (Bio-Medical Waste (Management and Handling) Rules 2016).

3 Strategies Adopted for Waste Management

There is a need to improvise waste management practices from a sustainable perspective. Sustainable development can only be achieved if humans stop misusing resources and minimize waste production and pollution. As part of waste minimization, many countries have started to follow recycling and reuse of materials and energy recovery from waste. The broadly accepted hierarchy of waste management helps in making strategies for waste management under different situations. Under this hierarchy, different approaches being adopted are waste reduction, recycling, waste processing, waste transformation and disposal (CPHEEO 2000).

3.1 Waste Education and Awareness

Educational institutions are sites of learning and the source of economic, cultural, recreational values and infrastructure (Lambert 2003). They are capable of influencing societal perception towards management of waste for earth's sustainability (Stephens et al. 2008). In any educational institution, education on waste and environmental awareness programme should be conducted for staff concerning issues on waste management and exercising on the strategies. Perception and behaviour are two components of environmental awareness. The perception of environmental problems depends on people's knowledge and moulds their behaviour towards environmental protection. Institutions such as educational and research institutions have a moral obligation towards society to act responsibly so as to protect the environment. With proper commitment, along with sufficient funding and infrastructure, educational institutions can become catalysts for responsible waste management.

3.2 Waste Reduction, Reuse and Recycling

First and foremost priority in waste management is minimisation of waste which includes reduction of generation of waste to the greatest possible extent and also reduction in toxic levels of the waste by proper treatment. This can be achieved by reduction in source utilization and implementing proper recycling activities. Waste production can be minimized at site of generation by following good housekeeping practices such as improving maintenance procedures, monitoring of leaking valves and fittings, maintaining proper material handling and transferring segregate waste streams, and tightening inventory controls. The manufacturing process can be modified to reduce waste generation.

Reuse of recyclable material is an efficient way of elimination of waste from the environment. Waste characterization study was carried out by Smyth et al. (2010) at the University of Northern British Columbia (UNBC) and they reported that institutional waste contains 49.34% recyclable, 28.42% non-recyclable and 21.61% compostable waste. Extensive segregation of reusable waste from the entire waste instead of discarding them can lead to substantial reduction in the total amount of waste generated. This strategy helps to conserve raw materials and energy that manufacturers use in producing new products and helps in the conservation of resources.

3.3 Waste Processing

Waste processing refers to the modification of waste so as to convert the waste into useful products so that it can significantly enhance waste management. During processing, there are two types of categorization that is followed, viz. sorting of waste at the source and centralized sorting. Sorting of waste from the source is still in its developing stage in India whereas centralized sorting which makes use of mechanized facilities is still lacking. Hand-sorting is still common practice since it is cheap and manpower is easily available in comparison to advanced and expensive mechanized facility. During treatment of waste with biological or non-biological process, useful products can be recovered such as compost or energy in the form of methane gas or electricity.

3.4 Waste Transformation

After completion of processing, the unutilised waste must be transformed through mechanical, thermal or other processes prior to its disposal. During mechanical transformation, bulky items are removed from the waste and shredded for reducing the size so as to enable better compaction of waste. Thermal transformation is generally implemented in regions with land scarcity. As no heat can be recovered from the waste with low calorific value, it may be combusted to reduce its volume. Other methods such as autoclaving, microwaving, hydroclaving, chemical fixation, encapsulation and solidification can be implemented to reduce the toxicity of waste, specifically biomedical waste.

A case study on institutional waste management was conducted in Jamalkhan Ward, Chittagong, Bangladesh wherein physical composition, characterization and rate of generation of waste were determined (Das et al. 2013; Hossain et al. 2013). Waste generated from different sources was separated and questionnaires prepared. Among the different institutions, waste generation by educational institutions was highest with 32%, followed by government institutions with 21.5%. Healthcare institutions were responsible for 17% of the waste generated, followed by religious institutions with 15% and private institutions with 14.5% of the waste generated. The waste coming out of the educational institution comprised of nine categories. Majority of the waste was paper waste (27%) followed by vegetable and food waste (25%). Healthcare institutions produced biomedical waste which comprised 5% of the total institutional waste. Bulk of the waste (50%) was recyclable.

4 Summary

Though the waste generated by the institutions is relatively lower than that generated by the industries and residencies, it is significantly hazardous and causes negative impact on human health and environment. Various strategies for waste management are being practiced throughout the world depending upon the feasibility and the economy. In developing countries like India, low cost waste management strategies such as dumping waste in landfills are being undertaken which in turn leads to the production of greenhouse gases that contribute to global warming. In order to mitigate environmental pollution issues and to improve the living standards of the individuals, awareness related to environmental issues and protection strategies should be created in the public. Educational institutions play a key role in spreading awareness and in implementing waste management strategies as they are under one authority and bound to some rules and regulations. Reduction in source utilisation for reducing waste generation, reusing recyclable materials and recovery of resources by using organic waste as animal feed or as feed material into compost or biogas production are potentially feasible strategies. In addition, funding, community sensitization on relevant issues, expertise and other facilities should be provided for implementing better management strategies.

References

Aira, M., Monroy, F. and Dominguez, J., 2007. Earthworms strongly modify microbial biomass and activity triggering enzymatic activities during vermicomposting independently of the application rates of pig slurry. *Sci. Total Environ.*, **385**, 252–261.

Chitnis, V., Chitnis, D.S., Patil, S. and Chitnis, S., 2002. Hypochlorite (1%) is inefficient in decontaminating blood containing hypodermic needles. *Indian Journal of Medical Microbiology*, **20**, 215–218.

Chitnis, V., Vaidya, K. and Chitnis, D.S., 2005. Biomedical waste in laboratory medicine: Audit and management. *Indian Journal of Medical Microbiology*, **23(1)**, 6–13.

Code, A. and Christen, J., 1999. How are we managing our healthcare wastes? SKAT, St. Gallen, Switzerland.

CPHEEO—Central Public Health and Environmental Engineering Organization, 2000. Manual on Municipal Solid Waste Management. Ministry of Urban Development, Govt. of India, New Delhi.

Da Silva, C.E., Hoppe, A.E., Ravanello, M.M. and Mello, N., 2005. Medical wastes management in the south of Brazil. *Waste Manage*, **25**, 600–605.

Das, S.R., Hossain, M.L., Salam, M.A., Talukder, S., Khanam, M., Aktar, F. and Hossain, M.K., 2013. Generation and Assessing the Composition of Commercial Solid Waste in Commercial City of Bangladesh. *Indian Journal of Engineering*, **2(5)**, 36–41.

Fricke, K., Santen, H. and Wallmann, R., 2005. Comparison of selected aerobic and anaerobic procedures for MSW treatment. *Waste Management*, **25**, 799–810.

Hossain, M.L., Das, S.R., Rubaiyat, A., Salam, M.A., Uddin, M.K. and Hossain, M.K., 2013. Characteristics and Management of Institutional Solid Waste of Jamalkhan Ward, Chittagong, Bangladesh. *International Journal of Research in Management*, **3(2)**, 155–162.

Ismail, S.A., 2000. Organic waste management. *In:* Technology Appreciation Programme on Evaluation of Biotechnological Approaches to Waste Management held on 26th October 2000. Industrial Associationship of IIT Madras.

Lambert, R., 2003. Review of Business–University Collaboration. HM Treasury, London.

Marinkovic, N., Vitale, K., Afric, I. and Janev, H.N., 2005. Hazardous medical waste management as a public health issue. *Arh Hig Rada Toksikol.*, **56**, 21–32.

Park, D.H. and Zeikus, J.G., 2000. Electricity generation in microbial fuel cells using neutral red as an electronophore. *Appl. Environ. Microbiol.*, **66**, 1292–1297.

Sarma, S.J., Brar, S.K., Le Bihan, Y. and Buelna, G. 2013. Bio-hydrogen production by biodiesel-derived crude glycerol bioconversion: a techno-economic evaluation. *Bioprocess and Biosystems Engineering*, **36**, 1–10.

SEMARNAT, 2003. General Law for Waste Prevention and Integrated Management. Diario Oficial de la Federación, Mexico.

Singh, J., Kaur, A., Vig, A.P. and Rup, P.J., 2010. Role of *Eisenia fetida* in rapid recycling of nutrients from biosludge of beverage industry. *Ecotoxicol. Environ. Saf.*, **73**, 430–443.

Smyth, D.P., Fredeen, A.L. and Booth, A.L., 2010. Reducing solid waste in higher education: The first step towards 'greening' a university campus. *Resources, Conservation and Recycling*, **54**, 1007–1016.

Stephens, J.C., Hernandez, M.E., Roman, M., Graham, A.C. and Scholz, R.W., 2008. Higher education as a change agent for sustainability in different cultures and contexts. *International Journal of Sustainability in Higher Education*, **9(3)**, 317–338.

Yan, S., Wang, P., Zhai, Z. and Yao, J., 2011. Fuel Ethanol Production from Concentrated Food Waste Hydrolysates in Immobilized Cell Reactors by *Saccharomyces cerevisiae* H058. *Journal of Chemical Technology and Biotechnology*, **86(5)**, 731–738.

Zhang, Y., Cheng, Y., Yang, C., Luo, W., Zeng, G. and Lu, L., 2015. Performance of system consisting of vertical flow trickling filter and horizontal flow multi-soil-layering reactor for treatment of rural wastewater. *Bioresource Technology*, **193**, 424–432.

Chapter 4
Scientific Approach for Municipal Solid Waste Characterization

Dirk Weichgrebe, Christopher Speier, and Moni Mohan Mondal

1 Introduction

1.1 Municipal Solid Waste Characterization

Knowledge of the composition of municipal solid waste (MSW) in specific rural or urban areas is of fundamental importance for the technical planning of waste collection, transport, recycling and treatment systems. Economic requirements, environmental influences and social impacts of waste management are projected and addressed within the system based on the waste composition. However, MSW is usually highly heterogeneous. Waste composition depends on consumption behaviour, housing structure, time, area, climate and other factors. Generation of reliable primary data on the composition of MSW appears to be difficult, time consuming and expensive. However, through an accurate statistical approach uncertainties in the technical planning are limited, and balanced with the required financial constraints for a characterization study. Apart from waste composition, profound and specific information on the generation of waste per person, behavioural aspects and local conditions are generated within the analysis.

Countries with emerging economies like India often employ complex waste management structures especially for collection and disposal of MSW. Local disposal behaviour, public waste management structures and climate or seasonal conditions influence the characteristics of waste streams. Hence, these impacts must be analysed and considered in order to determine reliable waste compositional data.

This chapter presents a systematic scientific methodology for the characterization of MSW using statistical methods (LuBB 1998; EC 2004; Büll et al. 2005;

D. Weichgrebe (✉) • C. Speier • M.M. Mondal
Institute of Sanitary Engineering and Waste Management, Leibniz Universität Hannover, Hannover, Germany
e-mail: weichgrebe@isah.uni-hannover.de

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_4

ISAH 2015). A step-wise approach includes preliminary investigation of the study area, development of a sampling strategy for data collection, execution of the study as well as evaluation and interpretation of the analysis as described in this paper.

List of Abbreviations

Cap	"per capita", here: per inhabitant
CDF	Cumulative Distribution Function
CI	Confidence Interval
B	Booth
DM	Dry Matter
FL	Filling Level
FM	Fresh Matter
GCV	Gross Calorific Value
GF_{21}	Gas Formation potential within 21 days
GIS	Geographic Information System
HD	High Density
HDPE	High-Density Polyethylene
HH	Household
LD	Low Density
MD	Medium Density
MSW	Municipal Solid Waste
NCV	Net Calorific Value
PET	Polyethylene Terephthalate
RA_4	Respiration Activity within 4 days
SB	Sampling Bin
STD	Standard Deviation
SWA	Solid Waste Analysis
TOC	Total Organic Carbon
W	Ward
WEEE	Waste of Electrical and Electronic Equipment
WG	Waste Generation

1.2 Definitions

Stratum/ Strata	A stratum or stratification parameter is a homogeneous sub-population (i.e., certain range of population per square kilometre) of a heterogeneous parent population (i.e., population density of the entire study area) created by statistical subdivision (EC 2004).
Waste streams	Waste collected with different collection types (i.e., curbside collection, commercial collection, street sweeping) are defined as streams.
Waste categories	Homogeneous sub-quantities of a mixed waste stream are separated on the basis of certain distinguishing features like the type of material (i.e., plastics, organics) defined as *primary*

	categories (i.e., organics), or further divided into sub-groups of the primary categories as *secondary categories* (i.e., yard waste, food waste).
Waste fractions	Sub-quantities of a waste stream defined by segregation criteria such as particle size, calorific value, etc. Particle size is usually obtained by sieving with different mesh sizes (i.e. 10, 60 and 80 mm).
Waste quantities	Waste amounts measured in terms of weight or volume. The waste is determined as an absolute value but can be expressed with respect to population, time or strata (i.e. kg/cap, kg/day or kg/cap/d).
Waste density	The density of waste describes its weight per volume. As the nature of waste is highly heterogeneous, the density of waste varies accordingly (i.e. organics ≈ 0.95 kg/l and plastics ≈ 0.03 kg/l).

1.3 Objectives of Waste Characterization

The main focus of a characterization study is to achieve the following objectives:

Waste composition

- Physical categorization and analysis of waste from different strata and waste categories
- Chemical analysis of waste from different strata and waste categories

Waste generation

- Obtaining strata-specific waste generation data
- Obtaining population-specific waste generation data

Waste Management

- Optimization of waste collection system (segregation, collection and transport)
- Selection of proper downstream waste treatment and recycling systems

2 Preliminary Investigation of the Study Area

The design of a statistically accurate plan for the characterization of solid waste requires a preliminary investigation of the study area and collection of data about the region, for example, the municipality and its jurisdiction, population, income groups, etc. Since MSW management is generally the responsibility of the local administration, acquiring information and data from the administrative authority is the first step in data collection.

Comprehensive data about the study area, population, building and settlement structure, as well as information about the current status of waste management are fundamental for a waste analysis study. Major issues for which data must be collected are listed in the following sub-sections. However, not all data is useful in all situations.

2.1 Study Area

The study area must be defined in terms of its administrative boundaries, topography, population, housing, and infrastructure. Data should be collected for the following:

- Regional, local, municipal, district and other administrative sub-divisions of the area, and determine physical boundaries of each sub-division,
- Topographical elements and land use (elevation levels, high/low vegetation rate, proximity to water bodies),
- Building types and layouts in the study area (apartment buildings, hut dwellings, individual houses, open/narrow settling structure, commercial or industrial areas),
- Infrastructural components (roads, electricity, water and sanitation infrastructure),
- Area characteristics (agricultural settling, industrial zone, office area), and
- Existing waste operation facilities (collection points, transfer stations, landfills, etc.).

2.2 Responsibilities and Regulations

- Responsible persons (for waste collection, treatment, management, supervision, environmental control authority, local and regional authorities)
- Stakeholders (private collection companies, formal/informal recyclers, treatment plant operators)
- Relevant regulations and legislations (MSW rules, emission standards, standards for waste handling, recycling rates, compost quality standards, municipal waste collection standards)

2.3 Population

- Total population
- Number of survey units (household, building, block, election booth, ward, district)
- Population per survey unit (household, building, block, election booth, ward, district)

- Income level
- Population density

2.4 Status of Existing Waste Management System

- Previous waste analysis studies
- Current waste management concept or action plan
- Waste type and quantity from each primary collection system (door-to-door collection, litter spots, drain cleaning, street sweepings)
- Waste segregation type and quantity (mixed waste, wet waste, recyclables)
- Waste collection type and quantity (littering, transfer with bins or bags)
- Collection efficiency and characteristics (number of persons with access to the collection system, share of collected waste compared to total waste generation, collection frequency, number and type of collection vehicles, number of waste management staff)
- Type and quantity of waste treatment and disposal (composting, combustion, landfilling)
- Waste generation per person/per survey unit and time (in kg/cap/day)

3 Stratification Methods

Based on the collected data, stratification of the study area into homogeneous sub-divisions is done. The aim of separating the study area into smaller sub-areas is to obtain higher accuracy of results with respect to waste generation in each stratum. With the same number of samples for the study area, a higher accuracy may be achieved through stratification. As a result, information on waste composition is not only available for the total collected waste stream, but also for each selected strata. Among various benefits, it allows direct comparison of the strata in terms of composition, quantity and density as well as development of strata-specific waste management systems. However, stratification of the study area is not mandatory for successful implementation of a waste characterization study, but rather recommended in order to improve the level of accuracy, detail and benefit for further technical planning.

3.1 Stratification Criteria

Many criteria that influence waste composition should be considered for stratification. Important stratification criteria that should be considered during stratification of any heterogeneous waste stream include:

- Residential structure,
- Population density,
- Seasonal variations,
- Type of collection system (separate collection), and
- Levels of public education and awareness on waste issues.

No universal criteria for stratification in waste analysis studies are recommended. However, stratification strongly depends on the structure and type of study area. The determination of strata should reflect the individual study objectives as well as an initial assessment of sub-populations. Moreover, it should address the major challenges and conditions on the ground. Potential stratification parameters are listed in Table 4.1.

3.2 Number and Types of Strata

The decision about the number of strata depends on data availability, requirements of the waste management system, municipal body and numerous other factors. It is recommended that the number of strata be limited to five or fewer. The application of more than five strata would require a higher number of samples and more effort without any significant effect on the accuracy of results (see Example 2).

Example 1
For the waste analysis study in Bengaluru City, population density was considered as the main stratification criterion. The first reason was the availability of election booth and Census data. The second reason was the overall linkage between population density and housing structure. The area was divided into three main population density areas, as shown in Table 4.2, to collect most representative samples:

Low density area	0–30,000 inhabitants/km^2,
Medium density area	30,000–70,000 inhabitants/km^2,
High density area	$>$70,000 inhabitants/km^2.

The study area was separated according to the selected stratification criteria using area and population data as shown in Fig. 4.1. The map also provides useful data for the estimation of waste collection and transfer systems in particular vehicle routes and transport of waste.

4 Sampling Design

The goal of sample design is to find cost-effective alternatives that balance the number of samples required and the statistical accuracy of results. In general, the total quantity of MSW is considered as the ‘parent population’ for statistical

Table 4.1 Potential parameters for the stratification of household and household-like solid waste

Stratification parameter	Explanation
Residential structure	Identical building/settlement types usually show similarities in waste composition:
	High apartment buildings
	Small apartments/Paying guest houses
	Individual/single houses
	Hut dwellings
	Mixed residential and commercial areas
	Suburban areas
	Rural areas
Collection/Disposal system	Separately collected or segregated waste streams are usually more homogeneous and suitable as strata:
	Door-to-door collection waste
	Litter spots waste
	Drain cleaning and street sweepings
	Organic waste
	Recyclables
Waste sources	Different waste generator types are recommended as sub-populations for sampling processes:
	Households
	Commercial entities
	Educational entities
	Institutional entities
	Municipalities
Population density	Separation of the study area in different densities of inhabitants per area must be evaluated. In urban areas in India high population densities correlate with low income levels. Hence, "population density" is an important parameter for stratification in India. However, it may be different in other countries and regions. An initial assessment is recommended to evaluate the suitability of this criterion.
Income level	Income levels may be correlated with varying waste composition. Areas like Bengaluru, India, with relatively high income level show a higher fraction of plastics and recyclables, while the organic fraction is higher in low income areas. However, income data are usually difficult to obtain, unless they can be correlated with a second criteria like residence type.
Seasonal variations	Different climatic periods can have a significant impact on the waste composition. In some regions of India, the moisture content of solid waste is much higher during the monsoon in comparison to the dry season. Additionally, different consumption behaviours with seasonal nature (e.g., wedding season in India) can influence waste composition and amount.
Bin size	The size of private waste receptacles is a common stratification parameter in industrialized countries. The study area may be stratified according to different bin sizes. However, due to low application of size-based bin collection systems in emerging economies, the feasibility of this parameter has to be evaluated.

Modified after EC (2004) and ISAH (2015)

Table 4.2 Stratification matrix – Distribution of samples taken within each stratum (ISAH 2015)

Sampling distribution	Strata	Low density (%)	Medium density (%)	High density (%)
		29.0	28.0	43.0
Door-to-door (%)	50.0	14.5	14.0	21.5
Street sweepings (%)	20.0	5.8	5.6	8.6
Litter spots (%)	30.0	8.7	8.4	12.9

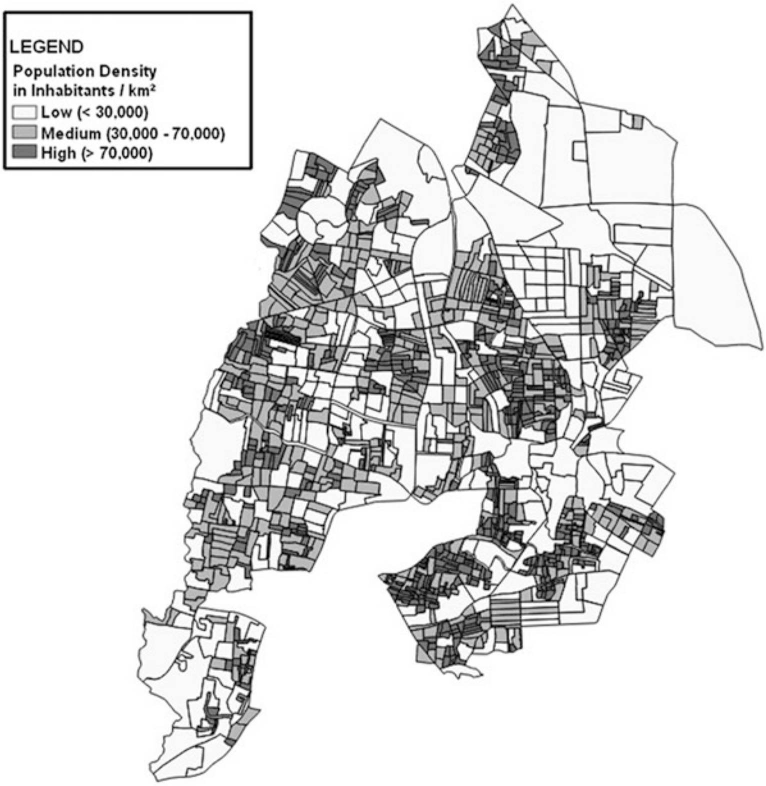


Fig. 4.1 Strata analysis and mapping for West Zone, Bengaluru (ISAH 2015)

purposes. This may include residual household waste, residual co-collected commercial waste, littered residual waste and/or street sweepings. A sample is defined as a representative sub-unit of the total or parent population. As it is not always possible to analyse the entire amount of waste from the study area, random samples from the parent population may be taken. It is important to ensure that a representative number of samples from the parent population are collected and analysed accordingly. The study area may be the entire area of a municipality or a defined part of a municipality which is representative of the whole area under investigation.

4.1 Type of Sampling

In the context of waste sampling, samples may comprise various types but must follow the rules of randomization. This allows probability statements on the quality of estimates to be derived from the resultant data. Sampling designs allow estimates of variability, the replicability of the study, and the ability to obtain valid conclusions. Five types of waste sampling designs are commonly used for normally distributed investigations (USEPA 2002):

- Simple random sampling
- Stratified random sampling
- Systematic sampling
- Ranked set sampling
- Sequential sampling

Regardless of the sampling method, a sufficient number of waste samples should be collected from the chosen strata. Guidelines for selecting a sampling plan are provided in Table 4.3.

Stratified random sampling shows benefit over other methods if the waste streams are highly heterogeneous. In stratified random sampling, a heterogeneous parent population is divided into non-overlapping sub-units called strata. Each stratum should be selected so that the variability within each stratum is less than the variability observed over the entire population (Gilbert 1987; USEPA 1992). Once each stratum is identified, simple random sampling may be applied to each stratum. For very heterogeneous wastes, stratified random sampling may be used to obtain a more efficient estimate of statistical parameters like mean or median, than may be obtained from simple random sampling.

4.2 Sampling Locations and Sampling Units

The *level of sampling* depends on the waste storage and collection system from which samples are collected. Waste samples may be collected from three major types of waste storage and collection processes (EC 2004):

- Internal waste bin (inside household/commercial property),
- External waste bin/container or community bin (outside household), and
- Secondary storage sites like litter spots or drains.

However, there are two major practical problems in sampling from internal waste bins/containers. Firstly, access to internal waste bins of private households is not ensured. Secondly, households must be informed in advance to gain access to internal waste bins. This may influence individual disposal behaviour.

The waste composition of secondary storage sites strongly depends on the storage duration. Longer storage times may result in an altered biological

Table 4.3 Guidance for selection of sampling plan or strategy

Sampling design	Appropriate conditions for use	Advantages	Limitations
Simple random sampling	Effective when the population of interest is relatively homogeneous (i.e., there are no major patterns or "hot spots" observed)	Provides statistically unbiased estimates of the parameters (i.e. mean, proportions, variance)	Less effective when patterns or trends are expected
		Easy to understand and implement	Localized clustering of sample points may occur by random chance
Stratified random sampling	Most useful to estimate statistical parameters of heterogeneous waste streams (i.e., major trends, patterns or hot spots are known to exist)	Ensures more uniform coverage of the parent population	Requires some prior knowledge of the waste or media to define strata and to obtain a more precise estimate of the mean
		Effective for obtaining high precision in estimates of the mean and variance	Statistical procedures for calculating the number of samples, the mean, and the variance are more complicated than for simple random sampling
		Enables computation of reliable estimates for population subgroups of special interest	
Systematic sampling	Useful for estimating spatial patterns or trends over time	Preferred over simple random method when sample locations are random within each stratum	May be misleading if the sampling interval is aligned with pattern contamination, which could happen inadvertently if there is inadequate prior knowledge of the pattern contamination
		Ensures uniform coverage of site, unit, or process May be lower cost than simple random sampling due to easier implementation	Not truly random, but can be modified through use of the "random within blocks" design
Ranked set sampling	Auxiliary variable (based on expert knowledge or measurement) is used to rank randomly selected units with respect to the variable of interest	Useful for reducing the number of samples required	Requires expert knowledge of waste or process, or use of auxiliary quantitative measurements to rank population units
		Can reduce analytical costs	

(continued)

Table 4.3 (continued)

Sampling design	Appropriate conditions for use	Advantages	Limitations
Sequential sampling	Applicable when sampling and/or analysis are quite expensive, sampling and/or measurement variability data are lacking, or when the waste and site characteristics of interest are stable over the sampling time frame	Can reduce the number of samples required to make a decision Allows a decision to be made with less sampling if there is a large difference between the two populations or between the true value of the parameter of interest and the standard	If the concentration of the constituent of concern is only marginally different from the action level, sequential procedures will require an increasing number of samples approaching that required for other designs such as simple random or systematic sampling

Modified after USEPA (1998) and (2002)

composition due to degradation processes. Additionally, valuables are more likely to be removed by informal recyclers.

For this reason, external waste bins/containers/bags or community bins are recommended as the level of sampling.

The *sampling unit* is the smallest unit of the total generated waste and accounted for in terms of volume, weight or population number. The selection of the sampling unit depends mainly on the availability of sampling bins. According to EC (2004), three main sampling units are used for waste sampling:

- *Volume* specific sampling units (i.e. 80, 120 litres),
- *Weight* specific sampling units (i.e. 100 kg), or
- *Population number* generating waste (i.e. 30 or 10,000 persons).

The sampling unit should be based on its *volume*. Sampling units must be of similar size for all strata.

4.3 Statistical Standards and Parameters

A representative sample must be chosen as comprehensive analysis of the total waste amount in the survey area is unfeasible. Therefore, the collected sample should be representative and statistically relevant for the investigation area. It should reflect the characteristics of the entire parent population. In general, MSW is highly heterogeneous and varies in sizes and composition. Thus it is necessary to determine a suitable sample size. The statistical standards and/or parameters must be defined at the outset to determine suitable sample sizes. The statistical parameters which are required for calculation of a suitable sample size are as follows:

- Confidence interval (95% recommended)
- Coefficient of variation (approx. 45–60%)
- Maximum allowance for random sampling error for the total results ($\leq$ 20%)
- Confidence coefficient (according to t-distribution table)

4.4 Calculation of Sample Size

The number of required sampling units depends mainly on the variation or heterogeneity of the waste streams which is commonly articulated by the coefficient of variation. The coefficient of variation of the samples refers to a relative measure of variability in which the standard deviation is expressed as a percentage of the mean. This coefficient of variation is normally unknown, but may be estimated from the results of previous waste analyses in the study area. Moreover, the required sample size is also defined by the desired accuracy of results for the total investigated waste streams. The necessary number of sampling units may be calculated using the following equation:

$$n = \frac{-N \cdot {t_{\alpha;n-1}}^2 \cdot \mathrm{var\,coeff}(x_i)^2}{\varepsilon^2 \cdot (-N+1) - {t_{\alpha;n-1}}^2 \cdot \mathrm{var\,coeff}(x_i)^2} \tag{4.1}$$

where n = minimum number of sample units, x_i = single value from the sample of waste fraction or category i, var coeff (x_i) = coefficient of variation of x_i, $t_{\alpha;n-1}$ = confidence coefficient, ε = random sampling error (RSE) and N = total number of units in Parent Population, Eq. (4.2)

$$N = \frac{WG_{\mathrm{vol \cdot cap \cdot day}} \left[\frac{\mathrm{m}^3}{\mathrm{cap \cdot day}}\right] \cdot \text{Total number of inhabitants in study area}}{\text{size of one sampling unit}\,[\mathrm{m}^3]} \tag{4.2}$$

$WG_{\mathrm{vol \cdot cap \cdot day}}$ = volumetric waste generation per inhabitant per day in $\left[\frac{\mathrm{m}^3}{\mathrm{cap \cdot day}}\right]$

When the coefficient of variation of the desired waste streams are known from previous studies, the necessary minimum number of sample units may be estimated by using Table 4.4. If there are no previous results available, the minimum number of samples is calculated using Eq. (4.1) with a coefficient of variation between 45% and 60%.

Example 2

The minimum number of required sample units is estimated by assuming the value of required statistical parameters. An example for the calculation is shown in Table 4.4. In this example, 10% maximum random sampling error, 95% confidence level and 50% coefficient of variation is assumed. The total minimum number of sample size units obtained is 91.

Table 4.4 Calculation of necessary number of sampling units

Coefficient of variation (%)	Necessary number of sampling units, n (95% confidence level) with maximum allowance for random sampling error (%)					
RSE→	*2.5*	*5*	*10*	*15*	*20*	*25*
15	127	34	9	4	2	1
20	213	59	15	7	4	2
25	309	91	24	11	6	4
30	409	127	34	15	9	6
35	508	168	46	21	12	7
40	604	213	59	27	15	10
45	693	260	74	34	19	12
50	775	309	91	42	24	15
55	849	358	108	50	29	18
60	916	409	127	59	34	22
65	976	459	147	69	40	26
70	1029	508	168	79	46	30
75	1077	557	190	91	52	34
80	1119	604	213	102	59	38
85	1156	649	236	114	66	43
90	1190	693	260	127	74	48
95	1220	735	284	140	82	54
100	1246	775	309	154	91	59

Note: Based on the volumetric waste generation $WG_{vol,\ Cap*day} = 1.5$ litres per inhabitant and day (ISAH 2015), a population of 1.66 million and a sampling unit size of 1 m^3 for the example of Bengaluru

In Fig. 4.2, a maximum allowance for random sampling error of 10% is considered when calculating the number of samples at a coefficient of variation of 20%, 30%, 40% and 50%. It is obvious that the number of required samples is not increasing significantly with an increasing population size after a certain point. As may be seen from Table 4.4, the required number of samples is 59 for a coefficient of variation of 40%, which is illustrated by Fig. 4.2.

4.5 Development of Sampling Plan

A suitable sampling plan is essential for achieving high precision in waste analysis results and their subsequent evaluation. The availability of a selection basis for the parent population of the waste analysis is considered as a pre-requisite for the preparation of a complete sample plan. Usually this is in an electronic database or spreadsheet format to ensure simple data evaluation (EC 2004).

It is essential to record the source of waste generation (i.e., address) either from the entire parent population or from relevant sub-populations. It is recommended that the random sample plan includes the preparation of a back-up set of sample

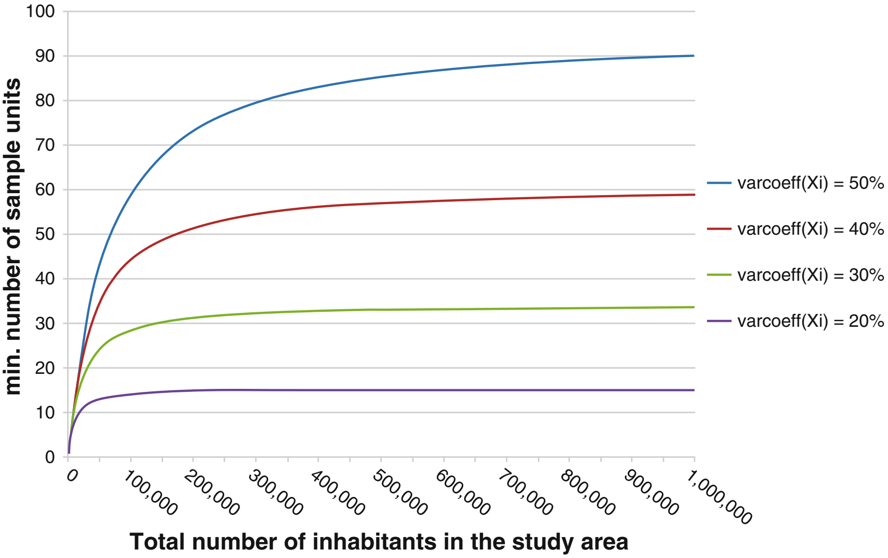


Fig. 4.2 Relationship of minimum number of samples vs. population size with respect to different coefficient of variation, for 10% random sampling error and a confidence interval of 95%

addresses (EC 2004). If the sample collector determines that it is infeasible to identify and collect the appropriate waste sample for analysis, the additional random sampling plan may be used instead of those primary addresses.

Example 3
Example of a stratified random sampling is illustrated in Fig. 4.3, which was developed for Bengaluru including 44 wards and a population of 1.66 million. The smallest unit of area was an election booth.

4.6 Duration of a Waste Characterization Campaign

It is suggested that the duration for waste sampling and sample collection covers a minimum of one week's waste in order to obtain information on daily variations. Since waste generation is also influenced by seasonal variations, waste characterization campaigns should be repeated at least twice per year depending on the impacts of variations.

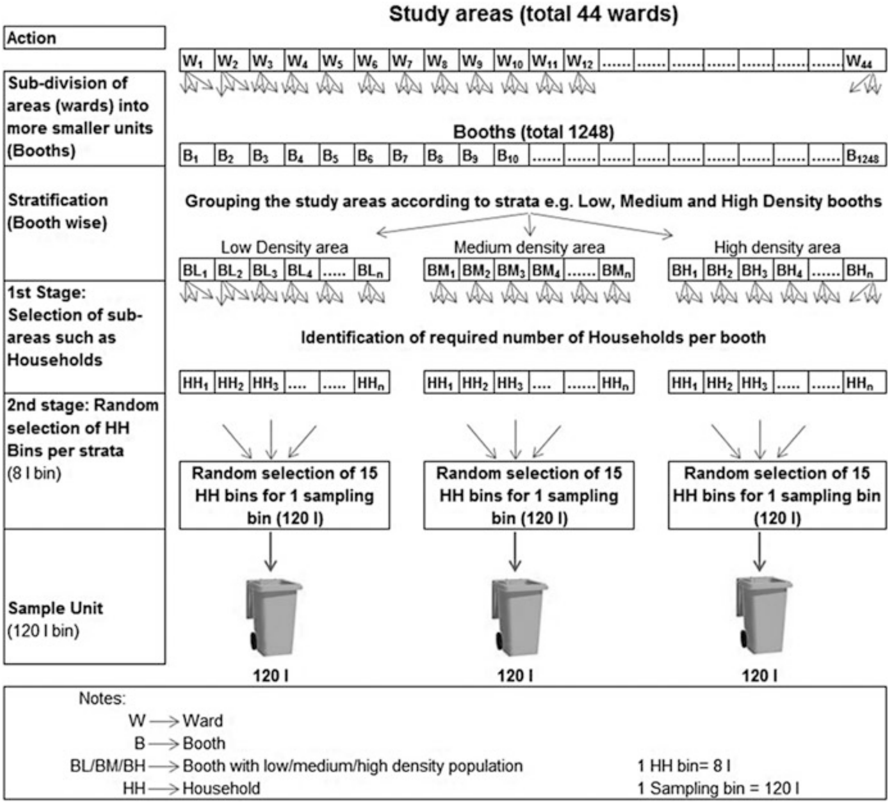


Fig. 4.3 Example of a stratified random sampling plan (ISAH 2015)

4.7 Preparation of Sorting Catalogue and Setting Screening Fraction Sizes

An extensive sorting catalogue must be developed before sorting of collected samples. Most visible or homogeneous physical categories are catalogued as primary categories which are further sub-categorized into secondary categories, i.e. resource recovery categories. However, the sorting catalogue may be adapted after initial sampling if some pre-determined categories are not detectable, or further separation into secondary categories would be beneficial. A preliminary investigation of the analysed waste stream or a plan in consultation with MSW Authority is recommended for the development of an adequate sorting catalogue.

Moreover, for sample processing, it is important to select screening fraction sizes beforehand as the physical analysis will follow accordingly.Screening devices may be a rotary sieve (trommels) or horizontal flat screens, both may be operated automatically or manually. To facilitate the screening process, automatic rotary screens are recommended. The inclination of rotary screen should not exceed 10°

(Weigand and Marb 2005) to maintain an adequate retention time of the material within the rotary screen. A high retention time increases the sieving efficiency. However, cascading movements of the material within the screen, which reduce screening efficiency significantly should be avoided. A cataracting motion is desired.

Example 4
For the study of Bengaluru, screening fractions with >80 mm, 40–80 mm, 10–40 mm and <10 mm were considered. An example of a sorting catalogue is shown in Table 4.5.

Table 4.5 Sorting catalogue used in Bengaluru city

Sl	Primary categories	Secondary categories
1	Organic wastes	Food waste
		Yard waste
		Other biodegradable
2	Wood	Untreated
		Treated
3	Paper	High gloss paper/card and wallpapers
		Paper/card – packaging
		Newspapers
4	Plastics	PET
		HDPE
		Low quality plastics
		Other hard plastics
5	Glass	Clear glass container (Packaging)
		Colour glass container (Packaging)
		Miscellaneous non-packaging glass
6	Textiles	Clothes (synthetic)
		Clothes (non-synthetic)
		Non-clothing textiles
7	Metals	Ferrous packaging
		Non-ferrous packaging
		Miscellaneous ferrous and non-ferrous
8	Household Waste	Batteries/Accumulators
		Miscellaneous hazardous waste
9	Composites	Composite/Complex packaging
		Composite/Complex non-packaging
10	WEEE	Waste of electrical and electronic equipment (WEEE)
11	Inert	Soil, stones and other inerts
12	Medical Waste	Medical waste
13	Fines	Fine fraction (e.g. <10 mm)
14	Liquids	Liquids

5 Sample Collection and Processing

5.1 Collection of Samples

Sample collection should be conducted without informing the waste generator, in order to avoid biased behaviour, especially for the collection of household waste. Individual samples should be tagged with a unique sample identification code or number, which is able to withstand wet or rough conditions. The following information should be organized and recorded for each individual sample by the sample collector during collection in order to ensure a transparent and comprehensible study (ISAH 2015):

For each sampling bin (SB), the following data must be recorded:

- Name and number of the sub-unit area
- Number of the sampling area
- Street names of sampling area
- Number of households per sampling bin
- Number of persons per sampling bin

In addition, for each sampling protocol the following data should be noted:

- Date of sampling
- Name of sampler
- Name of helper/present persons
- Name of the driver
- Registration or license number of waste collection vehicle

Moreover, during sample collection, the number of persons responsible for waste generation at the sample address and the collection interval should be recorded. If population data are not available, then general statistical information about the average number of persons per household may be available. This information is used to estimate waste generation per capita.

It is also very important to ensure that individual waste samples are not mixed with any other waste sample during collection, transportation and subsequent analysis. When the pre-determined and required number of samples for a characterization campaign have been collected, they should be transported to the appropriate facilities for sorting, screening and analysis.

5.2 Sample Processing and Data Recording

After transporting the full sampling bins to the sorting station, the weight of both filled and empty bins, the respective time and the filling level in (%) should be recorded and used later to determine the waste density. Additionally, the respective volume of the container has to be noted. This information should be noted on the data sheet 'weight before screening'. The waste density is calculated as follows:

$$\rho_{\text{waste}} = \frac{m_{\text{SB, filled}}\,(\text{kg}) - m_{\text{SB, empty}}\,(\text{kg})}{V_{\text{SB}}(\text{m}^3)FL(\%)} \tag{4.3}$$

where ρ_{waste} = waste density (kg/m^3), $m_{\text{SB, filled}}$ = weight of filled sampling bin (kg), $m_{\text{SB, empty}}$ = weight of empty sampling bin (kg), V_{SB} = volume of sampling bin (m^3) and FL = filling level (%).

After the screening process, the weights of the different size fractions have to be recorded, including the empty weight of each bin.

After the sorting process, the respective weights of all sorted sub-categories are recorded according to their particle sizes (i.e. >80 mm, 40–80 mm, 10–40 mm). All record sheets should be compiled in a suitable spreadsheet (i.e., Microsoft Excel) for further analysis.

5.3 Sorting and Screening

As part of sample processing, each sampling unit is weighed before and after screening. The weight is documented consequentially. Each sampling unit is sorted separately according to the categories mentioned in the physical sorting catalogue. The sorting catalogue contains primary and secondary waste categories. An example of the detailed procedure of screening and sorting for the Bengaluru waste analysis is illustrated in the following example and in Figs 4.4, 4.5 and 4.6.

Example 5
General screening and sorting procedure:

- The sampling unit is weighed; the weight m_i and the volume V_i are recorded along with respective filling level FL_i to determine the density ρ_i.
- In order to reduce the sorting effort, the sampling units are separated into predefined initial size fractions (i.e., $d > 80$ mm, 40–80 mm, 10–40 mm and $d < 10$ mm fractions are separated, by screening with the respective mesh sizes).
- Each size fraction (except fine fraction) are sorted into secondary categories as mentioned in the sorting catalogue and weighted afterwards.
- The secondary categories are combined with the primary waste categories according to the sorting catalogue. The weight of each primary category is recorded. Finally, the fine fraction (i.e. <10 mm fraction) is weighed; this value is recorded under the primary category 'Fines'.

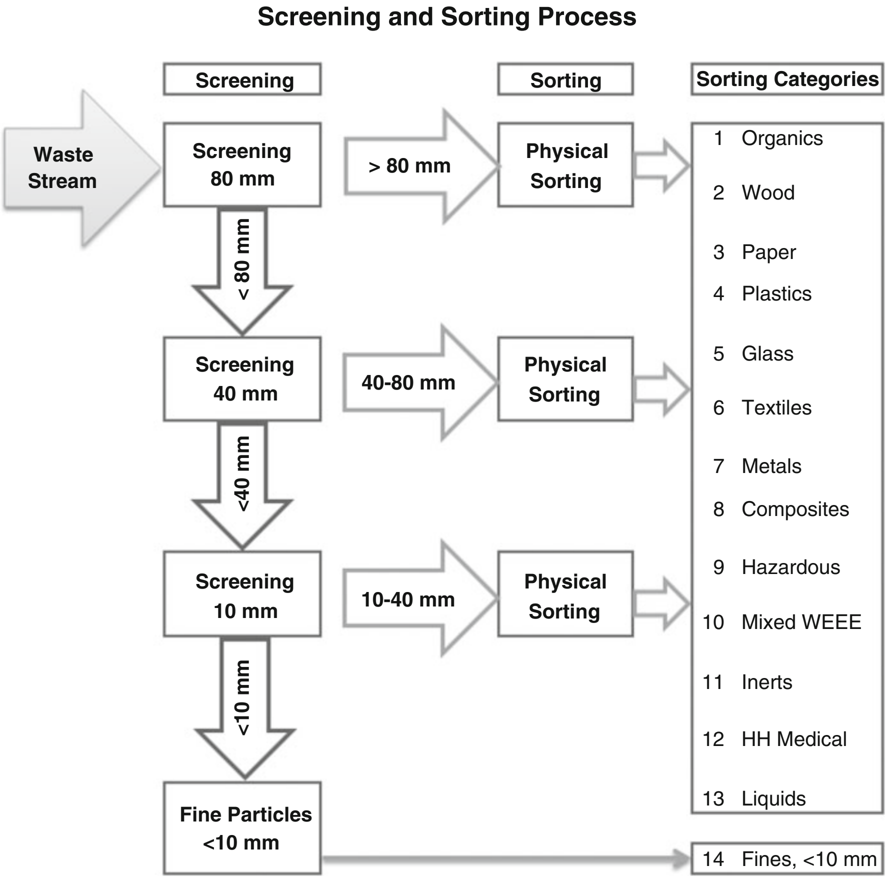


Fig. 4.4 Screening with three different mesh sizes and subsequent manual sorting (ISAH 2015)

5.4 Sampling for Biological and Chemical Analysis

The preparation of samples for chemical analysis is fundamental to obtain accurate results as MSW is highly heterogeneous with great differences in material sizes, types, distribution and composition. If the sample collection process neglects the heterogeneity of the material and reflects the chemical properties only of a local sample, the utilization and extrapolation of the results may be biased. Sample collection determines the quality of the results. It may be conducted in open, closed or moved material streams. The collection process should be adapted to the specific characteristics of the sampled material. Particle size, origin of samples, size of the parent population, type of sample material and level of detail of the required results influence the preparation and collection steps. With respect to further treatment options, high calorific value, water content, ignition loss, heavy metals and biological stabilization parameters as well as elution and leaching tests are recommended.

Fig. 4.5 Screening of collected samples into three fraction groups (ISAH 2015)

The Respiratory Activity within four days (RA_4) represents the aerobic degradability and stabilization and the Gas Formation Potential within 21 days (GF_{21}) represents the anaerobic degradability and biogas production of the waste sample. Thus composting or landfill behaviour can be predicted. The elution test analyses the leaching potential of the sample with respect to Total Organic Carbon (TOC), Ammonium ($NH^+{}_4\_N$), salts (Conductivity) and heavy metals (Pb, Cu, Cd, Hg) and other parameters.

The generation of mixed, combined and individual samples is recommended for the processing of samples for chemical analysis. If the total waste samples are separated into sub-quantities with different characteristics (size, shape, material composition), each sub-quantity must be sampled separately.

Example 6

In the City of Bengaluru, samples for chemical analysis were taken from each waste stream from different sieving fractions ($d > 80$ mm, 40–80 mm, 10–40 mm and $d < 10$ mm) and from six primary categories (organics, plastics, paper, composites, textiles, liquids).

For each sorting day, two individual samples were collected for each sub-quantity and stored in a refrigerator at 4 °C. After the end of each waste stream campaign, all grab samples from each sub-quantity were combined in a heap. The waste heap was coned and quartered into randomly mixed samples. Two laboratory

Fig. 4.6 Sample sorting into all primary and secondary categories (ISAH 2015)

samples of minimum of two litres were retrieved from each of the mixed samples. This implies that the minimum quantity of waste collected by grab sampling is eight litres.

The number of samples for each sub-quantity should be proportionate to the size of the total waste samples, i.e., as the volume of waste increases, the number and quantity of waste samples also increases. Minimum quantities of samples (grab and mixed) recommended for collection and analysis are shown in Table 4.6. The sample quantity must be evaluated for each case. If a higher accuracy is desired or additional criteria are of interest, a higher quantity of samples than required may be taken. Also, laboratory analyses should be accurate and performed in triplicate as waste is heterogeneous.

One mixed sample is retrieved from a minimum of four grab samples. The laboratory samples are retrieved from the mixed samples. The number of laboratory samples should be equal to the number of mixed samples. Additionally, the volume of the grab samples and the laboratory samples must be increased with increase in size of the waste materials in order to maintain high accuracy as shown in Table 4.7.

Each sub-quantity is mixed thoroughly and randomly. In order to achieve a high degree of homogeneity, various mixing methods are applicable (quartering, coning, shovelling, etc.). However, uncontrolled segregation by gravity during transport and storage must be considered.

Table 4.6 Minimum quantities of samples (LAGA 2004)

Volume of sub-quantity of waste	Number of grab samples	Number of mixed samples
<30 m^3	8	2
<60 m^3	12	3
<100 m^3	16	4
<150 m^3	20	5

Table 4.7 Volume of laboratory samples according to LAGA (2004)

Size range of waste materials	Minimum volume of grab samples (L)	Minimum volume of laboratory samples (L)
<2 mm	0.5	1
>2 mm to <20 mm	1	2
>20 mm to <50 mm	2	4
>50 mm to <120 mm	5	10

After the sampling process, the laboratory samples must be sealed and packed properly. Exposure to oxygen, light, heat, moisture or excessive turbulence during transportation should be avoided in order to prevent changes in the sample material. The time interval between sample collection and chemical analysis should be minimized. The sample receptacle should be air-tight and resistant to external forces and influences. To avoid biological degradation, the samples are stored and transported at a recommended temperature of 2–4 °C. If the samples are to be analysed for biological activity, the samples must be frozen at temperatures between -18 and -20 °C to prevent microbiological decomposition.

6 Statistical Analysis

6.1 Calculation of the Confidence Interval

The variance of the parent population is approximated by the variance of the waste sample. In standard cases, the *t*-distribution and the corresponding confidence coefficients ($t_{\alpha;n-1}$) are applied. The following step-by-step procedure is used to calculate the *confidence interval* for the Door-to-Door waste stream (EC 2004):

(a) Calculation of *mean* ($\bar{x}$) or *median* ($\tilde{x}$) from the sample

(b) The population *standard deviation* – STD (s) is estimated by the waste sample standard deviation

(c) Estimation of the *coefficient of variation of the mean*, using the following formula

$$\operatorname{var coeff}(\widetilde{x}) = \frac{s}{\widetilde{x}\sqrt{n}} \tag{4.4}$$

(d) Determination of the *confidence coefficient* (z-value)$_{t\alpha;n-1}$ from t-distribution table associated with the desired confidence level (i.e. 95%)

(e) Calculation of the *confidence interval* (CI) using the following formula:

$$CI = \bar{x} \pm \frac{\operatorname{var coeff}(x_i)}{\sqrt{n}} = \bar{x} \pm t_{t\alpha;n-1} \times \operatorname{var coeff}(\widetilde{x}) \tag{4.5}$$

Example 7
From the results for Bengaluru it was found that the sample mean for Door-to-Door waste is 24 kg with a confidence interval of ± 3.1 kg, as shown in Table 4.8. Intervals constructed this way contain the true value of the mean 95% of the time.

6.2 Distribution of Data Set and Subsequent Analysis

The distributional characteristics of a data set are fundamental for data analysis. If a sufficient number of samples are selected from the population, the distribution of the sampling data may be represented in the form of a histogram. A histogram offers a graphical representation of the data distribution curve, reflecting the number of points within each unit, and displaying the data as the height or area within a bar graph. Figure 4.7 is an example of a data set which follows a log-normal distribution in which the normal distribution is confirmed via probability plots of quantile or percent (Q-Q and P-P plot) and the cumulative distribution function (CDF) (Weichgrebe et al. 2015).

With a sufficiently large number of samples, the bars of the histogram can be transferred into a probability density function. Figure 4.8a is a normal distribution with a symmetrical shape. Figure 4.8b is a log-normal distribution in which the natural log-transformed values exhibit a normal distribution. A log-normal distribution indicates that a relatively small proportion of the population includes some extreme values.

In addition, the sample distribution may be analysed using box-whisker plots to show the ranges and outliers with a proper scale. Thus the relevant ranges of data as well as outliers are identified.

Example 8
An example box plot analysis for the waste samples of Bengaluru City is shown in Fig. 4.9 which ultimately follows a log-normal distribution.

Table 4.8 Calculation of sample mean, median, STD, CV and confidence interval (ISAH 2015)

Primary waste categories	Sample statistics of Door-to-Door waste stream (total sample size 78)						
	Min	Max	Mean	Median	STD (+/-)	var coeff($\widetilde{x}$)	CI (+/-)
	[kg]	[kg]	[kg]	[kg]	[kg]	[%]	[kg]
Average	15.2	34.4	24.0	23.5	5.3	15.0	3.1
Organics	150.1	261	203.8	209.7	30.1	3.9	17.4
Wood	0	2	0.5	0.2	0.7	34.6	0.4
Paper	23.2	36.6	28.7	27.7	3.7	3.5	2.1
Plastics	24.8	45.3	33	32.1	5.3	4.3	3.1
Glass	0.5	10.5	4.3	3.1	3	18.6	1.7
Textiles	3.5	29	13.7	10.3	8.5	16.5	4.9
Metals	0.5	2	1	0.9	0.4	10.8	0.2
Hazardous	0.2	6.2	1.4	1	1.4	26.7	0.8
Composites	5.1	18.7	9.6	8.6	4.1	11.4	2.4
WEEE	0	0.9	0.5	0.4	0.3	17.5	0.2
Inert materials	0.3	5.9	1.8	1	1.7	25.2	1
Biomedical waste	4.1	11.8	7.5	7.1	2.7	9.6	1.6
Fine particles	0	48.1	28.1	26.1	11.9	11.3	6.8
Liquids	0.3	3.1	1.4	1.4	0.8	15.5	0.5

STD Standard deviation, *CI* Confidence Interval, var coeff ($\widetilde{x}$) Coefficient of Variation of the mean

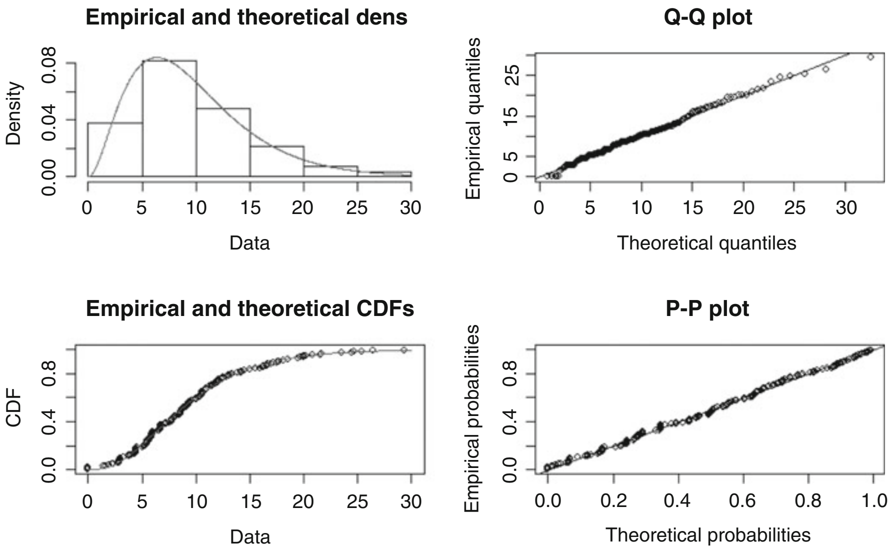


Fig. 4.7 Representation of data distribution using histogram and plots (Weichgrebe et al. 2015)

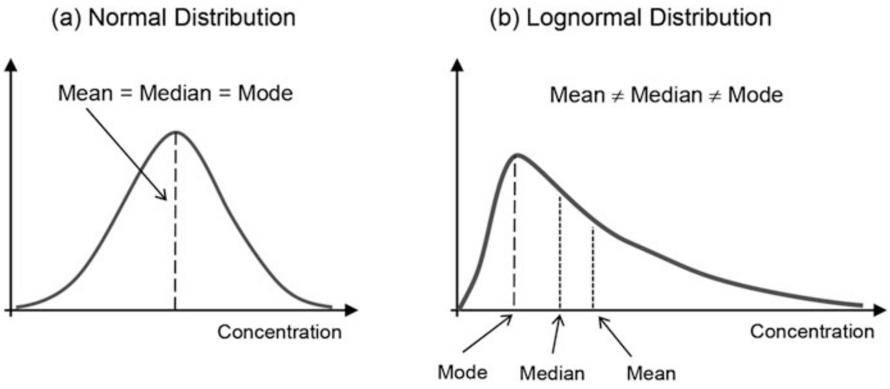


Fig 4.8 Example of (**a**) normal and (**b**) lognormal distribution (USEPA 2002)

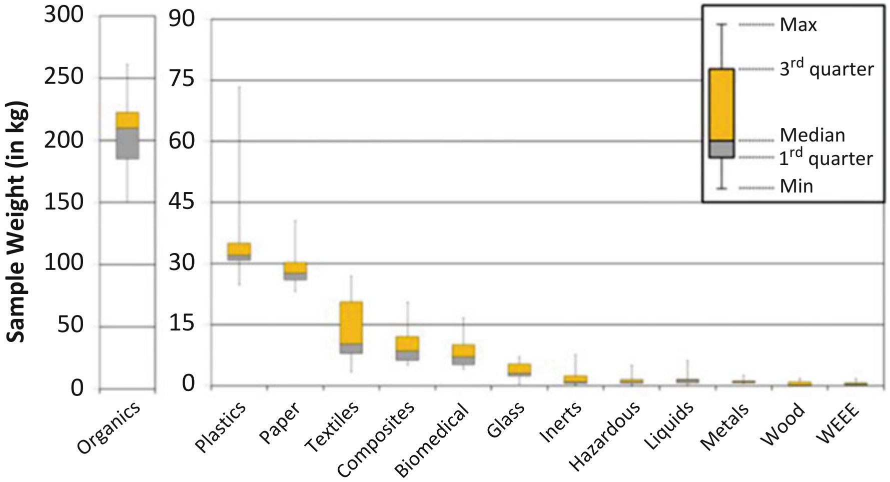


Fig. 4.9 Box plot of primary waste categories for Door-to-Door collection in Bengaluru (ISAH 2015)

7 Data Analysis and Interpretation

7.1 Interpretation of Physical Composition

The physical composition of the total waste as well as stream/strata-wise composition data can be analysed with all primary and (where feasible) secondary categories. The results of physical composition may be presented as tables, figures or graphs. Although a large amount of data is generated, it is recommended that the results be illustrated in a comprehensible way emphasizing specific key statements. The share of each of the primary waste categories is shown in Fig. 4.10 and

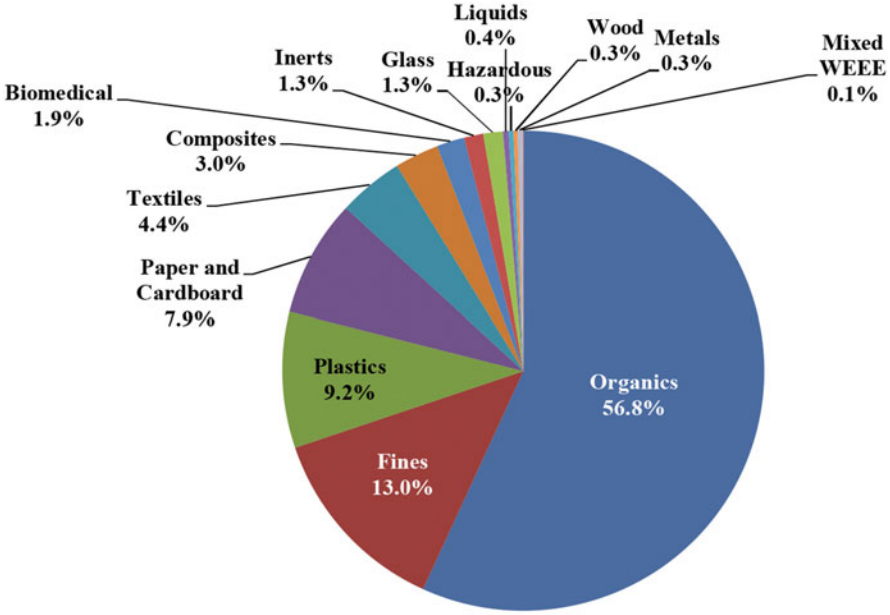


Fig. 4.10 Distribution of waste amount within primary categories, city of Bengaluru (ISAH 2015)

differences in waste composition between three size fractions and strata, low density (LD), medium density (MD) and high density (HD) for Bengaluru are shown in Fig. 4.11. The variations in organic, paper and textile contents between strata can be clearly observed.

Example 9

Figure 4.10 presents the primary categories of the waste analysis study in Bengaluru as a pie-chart to enable a direct comparison of mass shares of each category in the total waste amount.

Example 10

In the case of urban areas and megacities, characterization of a specific sub-quantity must be extrapolated to the entire area and population. For this reason, basic area information (Sect. 2.1) is required. Waste generation per capita is calculated as an average per strata by dividing the total sample weight by the sample population of that stratum (Table 4.9). Waste characterization for emerging economies usually requires a sub-quantity of the parent population in order to reduce the financial and coordination effort. The collected raw data must be transferred from the record sheet into a digital calculation file.

The results obtained for waste generation per capita and per strata were extrapolated for the total population per stratum and for the entire study area. Alternatively, the number of households or similar sampling units may be applied. For

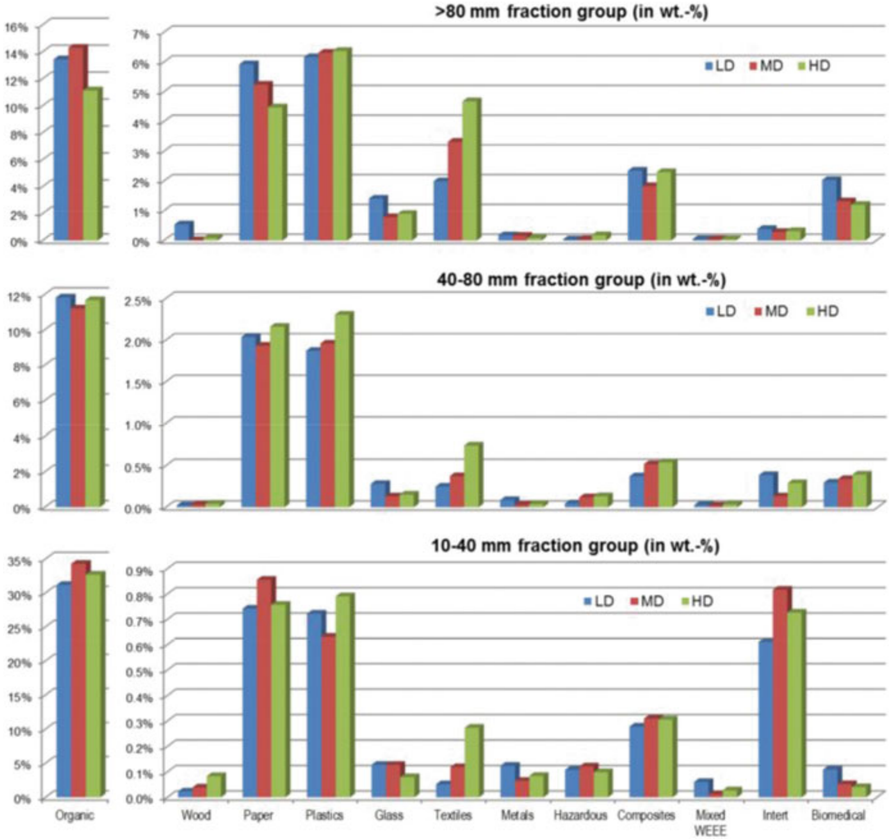


Fig. 4.11 Differences in waste composition between three size fractions and strata, city of Bengaluru (ISAH 2015)

Table 4.9 Extrapolation of total waste generation through per-capita waste generation (ISAH 2015)

	Door-to-door stream of West-Zone Bengaluru			
Strata	Sampled waste amount [kg/d]	Sampled population [cap]	Estimated per capita waste generation [kg/cap/d]	Extrapolation of total waste generation [ton/d]
Low Density	2364.0	4555	0.519	312.31
Medium Density	2679.6	6160	0.435	252.74
High Density	4392.3	11,178	0.393	350.65
All areas	9435.9	21,893	0.431	915.70

strata-specific waste generation data, the total population may be substituted by the population in each stratum.

$$WG_{\mathrm{cap,day}}\left[\frac{\mathrm{kg}}{\mathrm{cap}\cdot\mathrm{day}}\right]=\frac{\text{Waste weight sampled [kg]}}{\text{Population (persons sampled)}\cdot\text{time period }[d]}\tag{4.6}$$

The total generated waste streams may be projected for the study area or strata by applying the total or strata-wise waste composition in [%] to the total or strata-wise waste amount in [kg]. The variation coefficient in [%] must be applied simultaneously.

$$WG_{\mathrm{day}}\left[\frac{\mathrm{ton}}{\mathrm{day}}\right]=WG_{\mathrm{cap,day}}\left[\frac{\mathrm{kg}}{\mathrm{cap}\cdot\mathrm{day}}\right]\cdot\mathrm{Population}_{\mathrm{Total}}\tag{4.7}$$

Example 11
If the entire number of existing parameters per strata is not considered in the waste analysis, for example only two of four waste streams are investigated, the waste projection must be adapted accordingly to account for the missing data.

Additionally, waste generation may be plotted per unit area to enable improved planning of waste collection system. Area-specific population data is used to identify the waste amount per weight or volume generated in one specific area. If population data are available per house, block, booth or ward, an area map containing waste generation information may be created using geo-information systems (GIS). The requirements for waste collection vehicles and personnel are identified by combining these maps with topographical and infrastructural data. An example for GIS plotting of local absolute waste generation data is given in Fig. 4.12.

7.2 *Analysis and Interpretation of Biological and Chemical Characteristics*

All screened fractions and sorted categories have to be chemically analyzed in order to understand their composition with respect to water, organic and ash content. The *elemental analysis* results (Carbon, Hydrogen, Oxygen, Nitrogen, Sulphur, Phosphorous and Chloride) provide the basis for calculating further waste treatment processes: Carbon/Nitrogen/Phosphorous (C/N/P) ratio or Oxygen demand for biological treatment operation (i.e., from fine or organic fraction), Chloride, Nitrogen, Sulphur concentrations and calorific value for incineration.

The estimated *calorific value* of each fraction and category enables estimation of the energy potential of specific materials or mixtures. Gross calorific value (GCV), by definition, includes all the heat produced during combustion of any material including the latent heat of vaporization (required to convert water to steam). Net calorific value is defined as GCV minus the latent heat of vaporization as shown in Eq. (4.8) below (Worrell and Vesilind 2012). Net calorific value (NCV) is

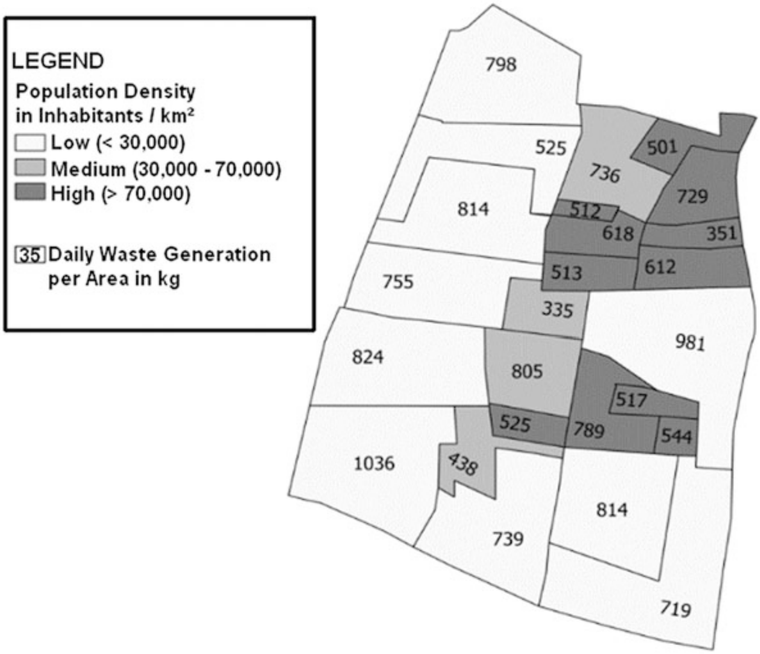


Fig. 4.12 Total daily waste generation for an example Ward (Basaveshwara Nagar, Ward 100, West Zone, Bengaluru) (ISAH 2015).

calculated for fresh matter (FM) from the relationship between Gross Calorific Value (GCV), moisture content and corresponding latent heat of vaporization ($\Delta h_v = 2.256$ MJ/kg) as below:

$$NCV\left[\frac{\text{MJ}}{\text{kg}}\right] = GCV\left[\frac{\text{MJ}}{\text{kg}}\right] - \Delta h_v\left[\frac{\text{MJ}}{(\text{kg H}_2\text{O})}\right] \cdot \text{Moisture content}\ [\text{kg H}_2\text{O/kg}] \quad (4.8)$$

The *heavy metals* content needs to be analysed to understand the possible environmental impacts of municipal solid waste, especially digestate or compost quality and potential leachate. *The respiratory activity* (RA_4) is conducted to evaluate the stability of waste according to the German landfill ordinance. The limit value for stabilized waste is 5 mg O_2/g DM that can be deposited in landfill (Dep 2012).

Example 12

As an example of waste analysis of Bengaluru, it can be seen that the C/N ratio of the organic fractions is approx. 22:1 which is not the optimum ratio (30–35) for an effective biological process like composting (Golueke 1972; Lens et al. 2004; Haug 1993). The carbon content for all fraction groups varies between 25–60%, hence further treatment for its reduction or transformation needs to be considered. Elemental compositions are summarized in Table 4.10.

Table 4.10 Elemental chemical composition of waste samples in Bengaluru (ISAH 2015)

GP mixed waste stream	Carbon (wt.-%)	Hydrogen (wt.-%)	Oxygen (% by diff.)	Nitrogen (wt-%)	Chloride (as Cl) (wt-%)	Sulphur (wt-%)	Phosphorous (as P_2O_5) (wt-%)
>80 mm	58.80	9.52	30.05	0.30	0.36	0.06	0.03
10–80 mm	30.78	6.87	60.70	1.67	1.90	0.15	0.20
<10 mm	26.16	5.53	67.07	1.33	1.95	0.10	0.11
Avg.	43.60	7.93	46.89	0.94	1.16	0.10	0.10
Organics	41.0	6.4	49.7	1.8	1.1	0.1	0.3
Paper	39.8	6.3	51.5	0.4	0.6	0.1	0.1
Plastics	63.4	10.8	22.9	0.4	0.8	0.0	0.0
Textiles	45.6	6.3	45.6	0.6	0.0	0.2	0.3
Composites	46.9	7.6	43.7	0.4	0.1	0.2	0.0

Most of the heavy metal values (data obtained as mg/kg of DM) of waste samples of Bengaluru are obtained at below the application limits of the Bio-Waste Ordinance of Germany/Europe as well as Indian compost quality standard. The exceptions are marked in Table 4.11 against corresponding standards. However, biodegradation processes will lower the organic and water content and hence the heavy metals will be concentrated.

The values of all analysed waste fractions in Bengaluru exceeded the given limit values for biological activity as mentioned in Table 4.12. Hence, direct disposal of these waste fractions on a landfill cannot be recommended to avoid damage to the landfill body and emissions due to biological conversion processes and reactions to landfill gas and leachate.

8 Tasks of Supervision

8.1 Health and Safety

MSW contains various health hazards. For this reason, the handling, sampling and sorting of the material must be conducted with caution. The study should be planned in a way that minimizes potential hazards and risks for the study personnel. The supervisor of the study is responsible for the safety of the entire staff, and must ensure that each worker regards safety rules, wears personal protection equipment and avoids risks.

Potential risks arise among others from the following influences:

- Insects and vermin attracted by waste (i.e., mosquitos, rats, stray dogs),
- Punctures and cuts through sharp objects (i.e., biomedical needles, glass, chemicals),
- Gases and explosive containers (i.e., aerosol bottles, deodorants),

Table 4.11 Chemical composition of waste samples with heavy metals contents in Bengaluru (ISAH 2015)

GP mixed waste stream	Heavy metals (based on dry matter)						
	Lead, Pb [mg/kg]	Zinc, Zn [mg/kg]	Arsenic, As [mg/kg]	Cadmium, Cd [mg/kg]	Copper, Cu [mg/kg]	Mercury, Hg [mg/kg]	Chromium, Cr [mg/kg]
German limit[a]	100–150	300–400		1–1.5	70–100	0.7–1	70–100
Indian limit[b]	100	1000	10	5	300	0.15	50
Waste Fractions (mixed waste from all strata)							
>80 mm	34.20	58.30	<0.1	<0.1	67.80	<0.1	21.75
10-80 mm	28.50	105.97	<0.1	<0.1	40.05	<0.1	17.75
<10 mm	13.60	122.40	0.90	<0.1	206.00	<0.1	18.35
Avg.	28.76	85.59	<0.1	<0.1	81.49	<0.1	19.79
Waste categories (waste from all strata)							
Organics	14.35	107.65	1.80	<0.1	160.35	<0.1	11.24
Paper	11.23	57.15	<0.1	<0.1	50.40	<0.1	7.80
Plastics	58.00	80.60	<0.1	<0.1	87.15	<0.1	40.10
Textiles	92.00	144.10	<0.1	0.80	283.55	<0.1	67.60
Composites	56.70	66.65	<0.1	<0.1	51.95	<0.1	36.65

▨ Exceeded both Indian and German limit ░ Exceeded Indian limit

[a] Ordinance on the recovery of Bio-Waste on Land used for Agricultural, Silvicultural and Horticultural Purposes (German/Bio-Waste Ordinance-BioAbfV 2013)

[b] Indian Standard of Municipal Solid Waste Compost, Manure Grade – Specification ICS No. 13.030.10, 65.080

Table 4.12 Summary of the RA_4 results

Sample waste streams	Oxygen uptake [mg O_2/g DM]				
	Moisture content [%][a]	>77 mm	14 – 77 mm	<14 mm	Limit value for waste disposal in landfill[a]
Door-to-door	50	15.0	19.4	5.8	<5
Litter spots	50	22.4	25.2	25.9	<5
Street sweepings	50	24.3[b]		12.8	<5

[a] As per German landfill ordinance (Dep 2009)
[b] Only for organic fraction

- Contact with biomedical waste, infections and pathogens (i.e., through respiration, contact with wounds),
- Heat and strong odour, and
- Hazardous waste and chemicals (i.e., heavy metals).

Protection equipment is recommended for every study participant to minimize accidents due to the above-mentioned risks. A personal protection set contains gloves which are water-resistant and durable, face masks, eye protection glasses, moisture-resistant aprons or jackets as well as firm and closed boots. The boots should also have an appropriate sole to avoid slipping on wet or uneven surfaces. Apart from personal protection, it is recommended to equip the study facility with a fire extinguisher, first aid kit, hand-sanitizer and disinfectants, towels and protection against vermin and mosquitos. The supervisor is responsible to prepare an openly available rescue and safety plan for the study area containing detailed information for the ambulance and fire department, safety information and guidelines to avoid accidents.

8.2 *Quality Control*

Although planned and prepared thoroughly, various problems may arise during a waste analysis study. As participants are often inexperienced, the supervisor has the responsibility to ensure a smooth process. This person is in charge of the sampling, screening and sorting process and must control and monitor each work step.

The supervisor must ensure that documentation for the sampling process is conducted properly. The number of households and waste generators must be noted adequately, and bins should be labelled appropriately. The supervisor must ensure that only relevant waste streams are sampled (i.e., no commercial waste during a household waste analysis). Additionally, sampling should be conducted according to the pre-determined random sampling plan. The supervisor is in charge of the entire screening and sampling process, the documentation and the coordination. It must be ensured that all weights are documented, that the sorting process is done with high accuracy and that spilling of sampling material is kept to a minimum. The supervisor must be prepared for expected and unexpected events and should avoid any deviation from the original study plan. However, deviations may be necessary to improve the accuracy of the study, and should be planned adequately.

In the following example, issues with respect to Quality Control are provided for different steps in a waste analysis study.

Example 13
In the city of Bengaluru, the following problems were observed.

Collection
For some households, the number of residents could not be recorded. In high density areas, it was not uncommon for large groups of people to simultaneously deposit their waste at the collection vehicle; this made accurate population counts impossible. In low density areas, some households kept their waste outside and were not at home at the time of collection. Moreover, waste storage in bins outside the houses led to increased moisture content during periods of rainfall (represented by seasonal effects). On some occasions, commercial waste found its way into the waste bins of Door-to-Door collection. Additionally, commercial waste might have also contributed to the waste of litter spots and street sweeping due to its unclear origin.

Sieving
Between emptying the collection bins and conveying the waste into the drum sieve, some liquid was lost during transfer although the floor was covered with tarpaulins. Fibrous material such as flower garlands, textile strands and ropes got wrapped inside the rotary sieve and was removed manually on a daily basis, which resulted in sample losses. Additionally, a minor amount of waste was spilled on the floor and counted as loss at the end of each sampling day.

Sorting
Due to lack of experience, few staff members may have sorted the samples without the desired precision. Proper sorting of the 10–40 mm and 40–80 mm fractions was difficult due to moisture. For example, paper was sometimes not separable from organic particles. On some occasions, the weights of intermediate samples was not recorded. Due to minor power outages, the refrigerator temperature for the chemical analysis samples could not be maintained at 4 °C all the time.

9 Rationale and Expected Outcomes

Through a scientific approach for solid waste characterization, in particular stratified sampling, the following outcomes are expected:

- Specific waste generation rates per capita may be determined and used as a basis for a comprehensive waste management which should be reviewed regularly, for example every five years.
- The segregation, collection and transfer methods of waste may be optimised by investigation of the waste categories and fraction. In particular, waste transport processes may be identified for the analysed area.
- Physical and chemical analysis of waste fractions will help in deciding which downstream treatment systems and recycling options for resource or energy recovery are feasible. In particular, the state of biological degradability and stabilization characteristics may be obtained to predict biological treatment efficiency or landfill behaviour.

Finally, associated environmental and health impacts may be explored and the costs of operation and investment are designated based on statistically verified data.

References

Büll, U., Zwisele, B., Nogueira, M. and Niestroj, J., 2005. Erhebung repräsentativer Planungsdaten für die Restabfallbehandlung eines Entsorgungsgebietes. Müll und Abfall, 1, 2005.

Dep, V., 2009. Landfill ordinance, April 2009 (BGBl.I p. 900), latest amendment March 2016 (BGBl. I p. 382).

EC, 2004. European Commission. Methodology for analysis of Solid Waste (SWA-Tool) User Version. iC consulenten ZT Gmbh, Austria. Retrieved from http://www.wien.gv.at/meu/fdb/pdf/swa-tool-759-ma48.pdf, Accessed on: 18.09.2014.

Gilbert, R.O., 1987. Statistical Methods for Environmental Pollution Monitoring. Van Nostrand Reinhold, New York.

Golueke, C., 1972. Composting – A Study of the Process and its Principles. University of California, Berkeley.

Haug, R., 1993. The Practical Handbook of Compost Engineering. Lewis Publishers.

ISAH, 2015. Institute for Sanitary Engineering and Waste Management Hannover. Municipal Solid Waste Characterization Study for West Zone, Bengaluru (unpublished).

LAGA, 2004. LAGA PN 98 Richtlinie für das Vorgehen bei physikalischen, chemischen und biologischen Untersuchungen im Zusammenhang mit der Verwertung/Beseitigung von Abfällen. Mainz, Germany.

Lens, P., Hamelers, B., Hoitink, H. and Bidlingmaier, W., 2004. Resource Recovery and Reuse in Organic Solid Waste Management. Integrated Environmental Technology Series. IWA Publishing.

LuBB, 1998. Landesumweltamt Brandenburg. Richtlinie für die Durchführung von Untersuchungen zur Bestimmung der Menge und Zusammenfassung fester Siedlungsabfälle im Land Brandenburg Teil 1. In Fachbeiträge des Landsumweltamtes Abfallwirtschaft, Titelreihe Nr. 34, Potsdam.

USEPA and USDOE, 1992. United States Environmental Protection Agency and United States Department of Environment. Characterizing Heterogeneous Wastes: Methods and Recommendations. EPA/600/R-92/033. NTIS PB 92-216894. EPA Office of Research and Development, Las Vegas, NV and USDOE Office of Technology Development, Washington, DC.

USEPA, 1998. United States Environmental Protection Agency. Final Technical Support Document for HWC MACT Standards, Volume VI Development of Comparable Fuels Standards. Office of Solid Waste and Emergency Response, Washington, D.C.

USEPA, 2002. United States Environmental Protection Agency. RCRA Waste Sampling Draft Technical Guidance Planning, Implementation, and Assessment. EPA/600/R-92/033. NTIS PB 92-216894. EPA Office of Research and Development, Las Vegas, NV and USDOE Office of Technology Development, Washington, DC.

Weichgrebe, D., Nguyet, T., Meier, S. and Kohlenberg, M., 2015. Ermittlung des tatsächlich bereitgestellten Restabfallvolumens in der Region Hannover (unpublished).

Weigand, H. and Marb, C., 2005. Zusammensetzung und Schadstoffgehalt von Restmüll aus Haushaltungen, Müll und Abfall 10, 2005.

Worrell, W., Vesilind, A. (2012) Solid Waste Engineering. 2nd Edition, SI Version. Cengage Learning, Stamford, USA. ISBN 978-1-4390-6217-3.

Zwisele, B., 2005. Probenahmemethoden für die Bestimmung von Menge und Zusammensetzung fester Abfälle. In: Müllhandbuch, Nr. 1661, Mai 2005.

Chapter 5
Characterization of Municipal Solid Waste (MSW): Global Trends

Prashanth Kandakatla, Ved Prakash Ranjan, and Sudha Goel

1 Introduction

Globally and in India, solid waste management is now a major environmental concern. It is now well-known that increase in the total amount of waste generated is directly proportionate to population growth and economic development. Municipal solid waste (MSW) includes refuse from households, waste from commercial establishments, and refuse from institutions, market waste, yard waste, and street sweeping (IBRD 1999). MSW usually contains food waste, paper, cardboard, plastics, textiles, glass, metals, wood, street sweeping, and tree trimmings, general wastes from parks, beaches, and other recreational areas. The composition of MSW varies according to consumption habits, income levels and standards of living among other factors (Annepu 2012). Global trends with regard to waste generation and composition are summarized in this chapter with greater emphasis on trends in India.

2 Generation of Municipal Solid Waste

There has been significant increase in MSW (municipal solid waste) generation in India in both, urban and rural areas. However, since the urban population is increasing at a much faster rate than the rural population, it is a major issue for urban local bodies to deal with. Urban MSW generation rates can be quantified in terms of total (tons/d) and per capita generation rates (tons/capita-d). In the absence

---

P. Kandakatla • V.P. Ranjan • S. Goel (✉)
Civil Engineering Department, Indian Institute of Technology Kharagpur,
Kharagpur 721302, WB, India
e-mail: sudhagiitkgp@gmail.com

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_5

of regular monitoring of waste generation rates, total waste generation rates are frequently estimated based on population size determined from Census data and estimates of per capita generation rates.

2.1 Total MSW Generation Rates in Urban Centres

Total MSW generated globally was estimated to be 1.3 billion tons/year and is expected to increase to 2.2 billion tons/year by 2025 (Hoornweg and Bhada-Tata 2012). Central Pollution Control Board (CPCB) in India estimated that the annual quantity of municipal solid waste generated in Indian cities has increased from 6 million tons in 1947 to 1948 million tons in 1997 with an annual growth rate of 4.25%.[1] Based on this growth rate, municipal solid waste is expected to increase to 402 million tons by 2047.

Ministry of Urban Development (MoUD), Government of India estimates that 1,00,000 MT of Municipal Solid Waste were generated daily in the country (MoUD, Government of India 2000). During the year 2004–2005, Central Pollution Control Board (CPCB) and National Environmental Engineering Research Institute (NEERI), Nagpur conducted a survey in 59 cities (35 Metro cities and 24 State Capitals) and estimated that 39,031 tons/day of MSW were generated in these cities/towns (CPCB 2013). During the year 2010–2011, CPCB and Central Institute of Plastics Engineering and Technology (CIPET) reported generation of 50,592 tons of MSW per day in the same 59 cities (CPCB 2013). This represents a 29.6% increase in MSW generation in 6 years. CPCB estimates from 2009 to 2012, show that 1,27,486 tons/day of MSW were generated in the country during 2011–2012, out of which 89,334 tons/day of MSW were collected (70%) and only 15,881 tons/d (12.5%) were treated (CPCB 2013).

Various methods for estimating total waste generation rates are available and include weight and volume-based measurement of waste generated. Load count analysis is another method that is frequently used to determine total waste generation rates.

2.2 Per Capita MSW Generation Rates

The average global per capita waste generation rate was estimated to be 1.2 kg/person-day (Hoornweg and Bhada-Tata 2012). Per capita MSW generation rates vary from 0.7 to 14.00 kg/person-day in high income countries but are as low as 0.6 kg/capita-day in low income countries. Per capita MSW generated daily in the different states of India ranged from about 157 g in Meghalaya to 475 g in Delhi and

---

[1] www.cpcb.nic.in

the average generation rate of MSW has been estimated as 0.376 kg/capita-day in a survey of 299 Indian cities by CPCB (Sharholy et al. 2008). It is important to note that per capita generation rates are estimates based on dividing total waste generated/day by total population. Measurements at the individual or household level will result in much smaller numbers since these do not include waste generated in common areas or public areas such as lawns, gardens, roads, street litter or from common services like sludges from municipal treatment plants, commercial and industrial waste.

3 MSW Characteristics and Composition

Waste characterization studies evaluating spatial and temporal variations are necessary for designing efficient systems and for predicting generation rates in the future. Waste characteristics and composition will change over time due to increased urbanization, consumerism and increase in standards of living.

MSW can be characterized based on its components or fractions and the elemental composition is generally determined for bulk, homogenized samples. No standard methods for characterizing MSW are available and the published literature has data that is reported without a detailed methodology. In many reports, different sampling and analytical methods have been used by different organizations and researchers making comparison across studies difficult.

3.1 Components of MSW

Waste composition is generally reported in the literature in terms of the major physical components of waste. The composition of MSW from various sources and collection points was determined on a dry weight basis and it consists mainly of a large organic fraction noted as compostable matter (33.4–78%), ash and fine earth (15–46%), paper (1.9–10%) and plastic (0.5–2%), glass (0.3–1.3%) and metals (0.4–3.6%). In a survey of 59 cities in India, the C/N ratio ranged between 14 and 53.0, and the calorific values ranged between 520 and 3766 kcal/kg (CPCB 2005). The physical characteristics of MSW in major metro cities in India are presented in Table 5.1. The methods used for determining these fractions or components were not reported.

In a related study, standard methods were used to determine the fractions or components of municipal solid waste and the results are shown in Table 5.2.

Examining data from different cities in different countries shows that waste composition varies significantly and is related to income levels, both at the individual level and higher levels like regions or countries (Kumar and Goel 2009; Hoornweg and Bhada-Tata 2012; IBRD 1999). Waste composition as a function of income level is shown in Table 5.3. The relative percentage of organic waste in MSW generally increases with decreasing socio-economic status. Paper, plastic,

Table 5.1 Physical composition of municipal solid waste from some cities in India (in per cent)

Cities	Paper	Plastic	Metal	Glass	Ash & earth	Total compostable
Puducherry[a]	3–7	0.57–0.86	0.4–1.0	0.29–0.76	31.7–46	33.4–41.7
Calcutta	3.18	0.65	0.66	0.38	34.00	47.00
Delhi	6.29	0.85	1.21	0.57	36.00	35.00
Chennai[b]	5.90	–	0.70	–	16.35	56.24
Nagpur	1.88	1.35	1.33	1.34	41.42	34.81
Bangalore	4.00	2.00	–	1.00	15.00	78.00
Bombay	10.00	2.00	3.60	0.2	45.60	40.00

All data (unless noted otherwise) from http://mospi.nic.in/comenv2000tab7.4.3.htm

[a] http://dste.puducherry.gov.in/envisnew/mswcomposition.htm

[b] http://wgbis.ces.iisc.ernet.in/energy/paper/Tr_114/tr_114pdf.pdf

Table 5.2 Summary of waste composition for Kharagpur city based on 20 samples from four different locations in the city

Component	Mean % (± standard deviation)	Parameter	% of total or wet weight
Plastic	1 (± 2)	Moisture content, %	42.05 (± 10.25)
Paper	7.76 (± 2.76)	Total solids, %	58.36 (± 11.57)
Glass	0.52 (± 1.28)	Volatile solids, %	19.63 (± 9.53)
Metals	0.004 ((± 0.018)	Fixed solids, %	80.35 (± 9.54)
Plastic bags	7.6 (± 2.6)	Total solids	100
Textiles	3.04 (± 2.4)		
Mixed residue	80.4 (± 4.6)	Organic carbon, %	8.92 (± 5.79)
Total	100	Calorific value, cal/g	2391.16 (± 264.58)

Source: Kumar and Goel (2009)

glass and metals are highest in higher income countries. As economic levels in low and middle income countries improve, there will be improvement in infrastructure and standards of living. The present trends indicate that the recyclables content, i.e., paper, plastics, glass and metals content will increase while organic content will decrease (IBRD 1999). Ash and earth content will decrease mainly due to increase in paved area. Although, organic content is expected to decrease, the material can still be biodegraded, provided it is segregated at source. High moisture content or low calorific value will continue to render the waste unsuitable for incineration.

3.1.1 Food Waste, Garden and Yard Waste

The largest organic fraction in MSW from developing countries is food (or kitchen) waste and garden and yard waste. Low- and middle-income countries have organic fractions that range from 41 to 60% of the total MSW (IBRD 1999). This fraction is also the most biodegradable and its presence in MSW makes the waste amenable to

Table 5.3 Types of waste composition by income level

Income level	Organic (%)	Paper (%)	Plastic (%)	Glass (%)	Metal (%)	Other (%)
Low income	64	5	8	3	3	17
Lower middle income	59	9	12	3	2	15
Upper middle income	54	14	11	5	3	13
High income	28	31	11	7	6	17

Source: Hoornweg and Bhada-Tata (2012)

composting. Segregation of this fraction at source is essential for all subsequent treatment strategies like composting or waste-to-energy generation (Goel 2008).

Leaf litter represents a significant proportion of the organic material in MSW. Litter decomposition is part of the natural carbon cycle, enhances the carbon content of soil and supports the saprophagic organisms in soil (Isaac and Nair 2005). Next to carbohydrates, lignin is the second most abundant component of plant litter and is also amongst the most bio-resistant components. "Lignin is a phenolic polymer composed of phenylpropene units. The most important components are vanillic, syringic, and cinnamic moieties. Lignin contents of wood range from 17 to 33% while leaves and needles contain less lignin, varying between 5 and 10%" (Miltner and Zech 1998). The presence of lignin in the cell walls of plant cells impedes enzymatic hydrolysis and subsequent biodegradation of plant carbohydrates Ko et al. 2009; Mosier et al. 2005; Sun and Cheng 2002).

In developing countries like India, the major organic fraction consists of food wastes from kitchens or vegetable shops, floral wastes from temples, ceremonies, and festivals, and yard waste. Low- and middle-income countries like India generate high percentage of organic matter which may vary from 41 to 60% of MSW (IBRD 1999).

Leaf litter and yard waste constitute a significant portion of the organic waste. Biodegradation studies with leaf litter and different grades of paper were conducted under anaerobic conditions and designed so that carbon was the only growth-limiting nutrient (Kandakatla et al., 2013). Leaf litter was found to be most resistant to biodegradation with approximately 75% degradation of total solids after 89 days, and approximately 53% decrement in tannin-lignin during the same incubation period. Newspaper and other grades of paper were less resistant to biodegradation compared to leaf litter despite their higher lignin content.

3.1.2 Paper

Paper is manufactured from wood pulp derived from various different hardwoods and softwoods. It is primarily made of lignocelluloses and characterization of 8 different plants (branches, stalks and whole plant) for cellulose, lignin and ash showed α-cellulose content ranging from 30.8 to 43.8% and lignin content ranging from 13.4 to 28.5% in these plants (Ververis et al. 2004; Tuomela et al. 2000). Efficient degradation of papers during composting requires biodegradation of lignin as well. However, lignin is often more difficult to biodegrade than cellulosic materials. Therefore, the biodegradability of organic waste depends to a large extent on the lignin content of the material.

Wood pulp which serves as the main raw material for most papers including newspapers is processed either mechanically and/or chemically to remove unwanted materials like resins, tannins, and lignin. The lignin content of pulp is not removed from newspaper, which is one of the lowest grades of paper. Higher levels of mechanical and chemical pulping are required to remove lignin and manufacture higher grades of paper. Acid-free paper requires complete removal of lignin and sulfur. Lignin and sulfur, both, promote acidic reactions in paper when exposed to light, high humidity, oxygen and atmospheric pollutants. Acidity causes the fibres to weaken and break and is the major culprit in causing regular paper to deteriorate and become discoloured (yellow) and brittle. Tannin-lignin content of newspaper was the highest (89 mg/g dry weight) while regular A4 printer paper and leaf litter had the least amount of tannin-lignin (13 mg/g dry weight) (Kandakatla et al. 2013). The tannin-lignin in newspaper was the most biodegradable compared to the other materials tested, i.e., leaf litter, A4 and magazine papers.

3.1.3 Other Recyclables: Plastics and Rubber

Plastic waste is a major environmental concern and its management is becoming increasingly difficult. Plastic is a cheap, durable and versatile material with varying degrees of strength and composition and has myriad applications. Today, plastics are used in every part of the economy from agriculture to automobiles, computers, packing materials, stationery, and water supply systems (Nithin and Goel 2017). Approximately 35% of the plastics used worldwide are for packaging applications (FICCI 2014). In the USA, 31 million tons (12.4%) of the MSW generated was plastic waste and 45% of that was plastic containers and packaging (USEPA 2014).

The life of plastic products is generally very small (roughly 40% have a service or useful life of less than one month) and depending on the area of application, the service life of plastic products ranges from 1 to 35 years (Panda et al. 2010). In the past two decades, several biodegradable plastics have been introduced into the market. However, none of them is efficiently biodegradable and therefore, none of these products has gained widespread use (Shah et al. 2008).

Rubber can be natural or synthetic (Practical Action 2010).[2] Natural rubber is obtained from a milky white fluid called latex, found in many plants, most notably the tree *Hevea brasiliensis*, which originates from South America (Scott 1999). Natural rubber (cis-polyisoprene) is highly bio-degradable and easily oxidized by sunlight. However, the long-term durability of discarded rubber tyres is mainly due

---

[2] http://practicalaction.org/docs/technical_information_service/recycling_rubber.pdf

to protective anti-oxidants added in the process of ‘vulcanization’ or ‘curing’ of rubber (Scott 1999). Synthetic rubbers (most are produced by copolymerization of styrene and butadiene) are produced from petroleum and 2/3 of the total rubber produced globally is now synthetic in nature.[3] Most of the rubber is reused or recycled in various products like shoe soles, containers, instruments, and non-pneumatic tyres for wheels.

3.1.4 Floral Waste

China is the largest flower producer in the world followed by India. According to the latest data of the National Horticulture Board (NHB) for 2012–2013, 233,000 hectares was used for floriculture in India, resulting in the generation of 17,29,000 metric tons of loose flowers and 76,732 lakhs cut flowers (NHB 2011). Given the perishable nature of flowers, floral waste constitutes a major fraction of organic solid waste especially in urban areas.

Flowers are an integral part of all religious and cultural ceremonies and floral waste is generated from various sources like hotels, marriages halls, gardens, temples, churches, dargahs and during cultural and religious ceremonies and festivals. The bulk of flowers are piled up and then disposed in open dumps or are released into rivers and other surface water bodies (Singh et al. 2013). Because of our religious beliefs, many avoid throwing flowers and other items that are used for prayers in the garbage, and instead put them in plastic bags and throw them directly in the water bodies since there is no other suitable mode for disposal. Varanasi (Banaras), one of the holiest cities in India, has no policy for disposal of the tons of floral waste that come from its many temples. Each day, waste material weighing 3.5–4 tons is left behind in the city of temples (Mishra 2013).

In India, there are many other holy places like Badrinath, Kedarnath, Haridwar-Rishikesh, Mathura-Vrindavan, Ayodhya, and Varanasi/Kasi, where thousands of devotees come every day to pay their obeisance to almighty God by offering flowers. These huge amounts of offered flowers create a large amount of flower waste which are released into the water bodies or dumped on available land and create severe environmental pollution and health hazards. It is said that on any given day, more than 200 kg of flowers are offered to Lord Ganesh at Khajrana Temple which goes up to 1000 kg/d during the festive season (Jha 2015). Thus, this waste is generally neglected and needs more attention.

Flowers have a very high C/N ratio, low calorific value and very high moisture content. Their biodegradation was examined under both aerobic and anaerobic conditions. No significant differences in their biodegradability were observed under the two conditions (Ranjan 2016).

---

[3] https://en.wikipedia.org/wiki/Synthetic_rubber

Table 5.4 Chemical characteristics of MSW in Indian cities

Population (in millions)	Nitrogen as total nitrogen	Phosphorus as P_2O_5	Potassium as K_2O	C/N ratio	Calorific value, kcal/kg
0.1–0.5	0.71	0.63	0.83	30.94	1009.89
0.5–1.0	0.66	0.56	0.69	21.13	900.61
1.0–2.0	0.64	0.82	0.72	23.68	980.05
2.0–5.0	0.56	0.69	0.78	22.45	907.18
>5.0	0.56	0.52	0.52	30.11	800.70

Calorific value on dry weight basis
Source: Sharholy et al. (2008)

3.2 Chemical Composition of MSW in India

The chemical composition of MSW is dependent on several factors such as income at the individual or larger scales, resource consumption which in turn depends on degree of economic development, recycling options, economic incentives for resource conservation, location and related geographic factors like climate, and precipitation.

The elemental composition of MSW is very important since it determines the nature of processing, treatment and disposal options available for handling that waste. The presence of toxic heavy metals in MSW can lead to inhibition or complete shutdown of any biological process for producing biogas or compost. In general, cost of proximate analyses or elemental composition of any material is prohibitively expensive and most literature reports are limited to C, N, P and K measurements, if any. A summary of available data for N, P and K along with calorific values for Indian cities is provided in Table 5.4 and is based on a NEERI strategy paper published in 1995 (Sharholy et al. 2008).

Similar data from other countries or cities is lacking and highlights some of the major gaps in characterizing municipal solid waste around the world.

4 Conclusions

Proper management of MSW requires regular monitoring and characterization of the waste being generated, collected, treated and disposed. In most locations, waste quantities generated or collected are estimates based on population data and very little characterization data are available in the published literature or in the public domain. Physical composition of waste is easier to determine as compared to chemical and biological characterization of waste. All of the data in the published literature is based on physical characterization rather than chemical or biological characterization. Another major issue is the lack of globally acceptable standard methods for characterizing MSW.

References

Annepu, R.K., 2012. Sustainable Solid Waste Management in India. Department of Earth and Environmental Engineering at Columbia University.

CPCB, 2005. Management of Municipal Solid Waste Management, 1–27.

CPCB, 2013. Status Report on Municipal Solid Waste Management.

FICCI, 2014. Potential of Plastic Industry in Northern India with Special Focus on Plasticulture and Food Processing 2014: A report on plastics industry. Retrieved from http://ficci.in/spdocument/20396/Knowledge-Paper-ps.pdf.

Goel, S., 2008. Municipal Solid Waste Management (MSWM) in India: A Critical Review. *Journal of Environmental Science and Engineering, NEERI*, **50(4)**, 319–328.

Hoornweg, D. and Bhada-Tata, P., 2012. What a Waste: A Global Review of Solid Waste Management. Urban Development Series Knowledge Papers. Washington DC, USA. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/25270340.

IBRD, 1999. What a Waste: Solid Waste Management in Asia. Washington, DC.

Isaac, S.R. and Nair, M.A., 2005. Biodegradation of leaf litter in the warm humid tropics of Kerala, India. *Soil Biology and Biochemistry*, **37(9)**, 1656–1664.

Jha, B., 2015. Waste management: Khajrana temple shows the way. *The Times of India*. Retrieved from http://timesofindia.indiatimes.com/city/indore/Waste-management-Khajrana-temple-shows-the-way/articleshow/49514202.cms

Kandakatla, P., Mahto, B. and Goel, S., 2013. Extent and rate of biodegradation of different organic components in municipal solid waste. *International Journal of Environment and Waste Management*, **11(4)**, 350–364.

Ko, J.-J., Shimizu, Y., Ikeda, K., Kim, S.-K., Park, C.-H. and Matsui, S., 2009. Biodegradation of high molecular weight lignin under sulfate reducing conditions: Lignin degradability and degradation by-products. *Bioresource Technology*, **100(4)**, 1622–1627. doi.org/10.1016/j.biortech.2008.09.029.

Kumar, K.N. and Goel, S., 2009. Characterization of Municipal Solid Waste (MSW) and a proposed management plan for Kharagpur, West Bengal, India. *Resources, Conservation and Recycling*, **53(3)**, 166–174. doi.org/10.1016/j.resconrec.2008.11.004.

Miltner, A. and Zech, W., 1998. Beech leaf litter lignin degradation and transformation as influenced by mineral phases. *Organic Geochemistry*, **28(7)**, 457–463.

Mishra, N., 2013. Unholy mess: Temple waste, a concern. *The Times of India*. Retrieved from http://timesofindia.indiatimes.com/city/varanasi/Unholy-mess-Temple-waste-a-concern/articleshow/21872439.cms.

Mosier, N., Wyman, C., Dale, B., Elander, R., Lee, Y.Y., Holtzapple, M. and Ladisch, M., 2005. Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresource Technology*, **96(6)**, 673–686. doi. doi.org/10.1016/j.biortech.2004.06.025.

MoUD, Government of India, 2000. Advisory on Improving Municipal Solid Waste Management Services.

NHB, 2011. Indian horticulture database – 2010. Gurgaon.

Nithin, B. and Goel, S., 2017. Degradation of Plastics in Advances in Solid and Hazardous Waste Management. Capital Books and Springer.

Panda, A.K., Singh, R.K. and Mishra, D.K., 2010. Thermolysis of waste plastics to liquid fuel: A suitable method for plastic waste management and manufacture of value added products—A world prospective. *Renewable and Sustainable Energy Reviews*, **14(1)**, 233–248. doi.org/10.1016/j.rser.2009.07.005.

Ranjan, V.P., 2016. Rate and extent of batch biodegradation of floral waste. M.Tech. Thesis, IIT Kharagpur.

Scott, G., 1999. Polymers and the environment (First ed.). Royal Society of Chemistry. Cambridge, UK.

Shah, A.A., Hasan, F., Hameed, A. and Ahmed, S., 2008. Biological degradation of plastics: A comprehensive review. **26**, 246–265. doi.org/10.1016/j.biotechadv.2007.12.005.

Sharholy, M., Ahmad, K., Mahmood, G. and Trivedi, R.C., 2008. Municipal solid waste management in Indian cities: A review. *Waste Management (New York, N.Y.)*, **28(2)**, 459–467. doi.org/10.1016/j.wasman.2007.02.008.

Singh, A., Jain, A., Sarma, B.K., Abhilash, P.C. and Singh, H.B., 2013. Solid waste management of temple floral offerings by vermicomposting using Eisenia fetida. *Waste Management*, **33(5)**, 1113–1118.

Sun, Y. and Cheng, J., 2002. Hydrolysis of lignocellulosic materials for ethanol production: A review. *Bioresource Technology*, **83(1)**, 1–11. doi.org/10.1016/S0960-8524(01)00212-7.

Tuomela, M., Vikman, M., Hatakka, A. and It, M., 2000. Biodegradation of lignin in a compost environment: A review. **72**, 169–183.

USEPA, 2014. Municipal solid waste generation, recycling and disposal in the United States: Facts and figures for 2012.

Ververis, C., Georghiou, K., Christodoulakis, N., Santas, P. and Santas, R., 2004. Fiber dimensions, lignin and cellulose content of various plant materials and their suitability for paper production. Industrial Crops and Products, **19(3)**, 245–254. doi.org/10.1016/j.indcrop.2003.10.006.

Chapter 6

Applications of Remote Sensing and Geographical Information System (GIS) in Assimilation of Environmental Data

Debasis Deb

1 Introduction

Remote Sensing (RS) is the science and art of obtaining information about an object without touching or changing the object, specifically, the Earth's surface or atmosphere (Lillesand et al. 2004). Remote Sensing is basically used by the scientific community for mapping and monitoring of natural resources on the surface of the earth. Remote sensing images provide reliable surface information for large spatial areas. The satellite images of an area are records of its changing hydrogeomorphology over time. In India, National Remote Sensing Centre (NRSC), Hyderabad maintains databases of earth surface images using various sensors, viz. PAN, LISS I, LISS II, LISS III, OCM, WIFS, and AWIFS. Satellites providing images are IRS-1A, 1B, 1C, 1D, P5, P6 and OCEANSAT. India currently has 5 Cartosat satellites (1, 2, 2A, 2B, and 2C) with resolution ranging from 1 m (Cartosat-2) to the most recent one (Cartosat 2C launched on 22 June 2016) providing images with resolution of 25 cm.[1] These high resolution images can be effectively used for making digital elevation models (DEM), water resources management and several other applications.

Geographic Information Systems (GIS) can be defined as an organized collection of computer hardware, software and geographic data designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information. GIS possess strong capacities for database management and graphical representation, especially when the data are spatially related. GIS can be used to pre-process data of various disciplines from large databases into a form

---

[1] https://en.wikipedia.org/wiki/Cartosat

D. Deb (✉)
Mining Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: deb.kgp@gmail.com

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_6

suitable for analysis, to provide direct support for modeling and to process the results, including tabulation, mapping and report generation. Therefore, with GIS, it is not only more convenient but also it is illustrative and convincing to manage research output or to make visual and dynamic decisions. This technique is a leap forward from the traditional way of analysis and presentation of spatial data. In a broad sense, GIS helps the user make more informed decisions (Belward and Valenzuela 1990). GIS is also used to generate thematic maps and queries based on the geographic locations and attribute data, for example with the digitized settlements, one can generate a query stating "*Find the settlements that are located within 5 km radius of power plants*". Now if the information of households is available, more detailed queries can also be generated to evaluate their health status, education level, social status and others. The detailed procedure of GIS-based data management is explained in Fig. 6.1. Several GIS software are commercially available such as ArcView 3.x, ArcGIS, ArcSDE, ArcIMS, ArcWeb, GeoMedia, GeoMedia Professional, GeoMedia WebMap, MapInfo Professional MapXtreme, MapGuide and AutoCAD. Image processing softwares such as MultiSpec Image Processing, ScanMagic, ScanEx Image Processor, ScanEx SAR Processor, ScanEx NeRIS, ERDAS IMAGINE, MB-System, and Geomatica FreeView are also used in conjunction with GIS software to edit/manage satellite images and to convert them to GIS platform.

Four case studies are presented in this chapter where environmental data are analysed and assimilated using RS and GIS application software. High resolution DEM was developed from CARTOSAT-1 stereo data to extract cross sections of the Subarnarekha River at several locations for analysis of river runoff during flood year of 1997. Hydrodynamic modelling of the Subernarekha River was carried out for development of water surface profiles and discharges along the reaches of the Subernarekha River. Validation of hydrodynamic modeling has been carried out

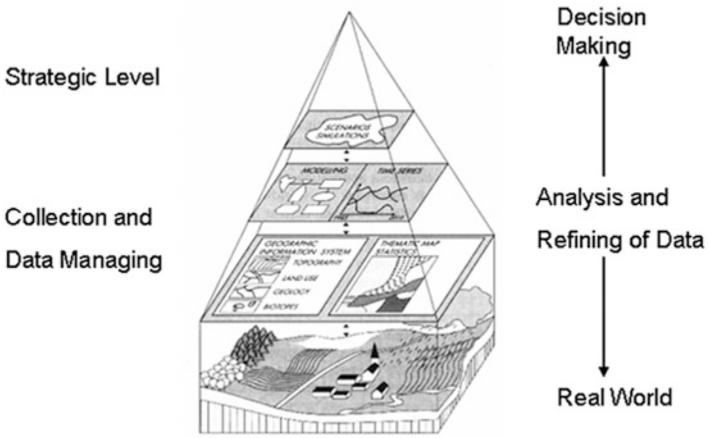


Fig. 6.1 Schematic diagram of GIS based data management

using error functions like coefficient of efficiency, percentage deviation in peak, and index of agreement. Flood inundation mapping and damage due to floods was estimated in GIS platform for different land use and land cover classes such as agriculture land, habitats, dense forest, mixed vegetation, plantation, scrubs, water bodies and barren rock. Land use and land cover changes have been estimated in the Korba mining and industrial area for about 10 years using image processing and GIS techniques. The overall accuracy of land use and land cover (LULC) lies in the range of 85–89%. From this study, it was observed that there was 50.7% reduction in forest cover from 1995 to 2004. This study was extended to detect coal fires in the Gerva coal mine using Thematic Mapper (TM) images. It is estimated that the maximum temperature of burning coal can reach as high as 190 °C. Lastly, thematic mapping of ground water data, forest diversity index and demographic information can be presented on a GIS platform to show the efficacy of GIS in storing, managing and retrieving of data and images.

2 Applications of Remote Sensing and GIS

Remote sensing techniques and data products are gaining importance in urban, regional, and environmental studies. This is due to the speed and cost-effectiveness in mapping and monitoring urban growth, and land use apart from providing timely, repetitive and synoptic coverage of urban and rural areas (Roy et al. 2001). The technology of remote sensing, both aerial and satellite based systems allows physical information to be collected easily with speed and on a repetitive basis. Along with GIS, it can be used to analyze the data offering possibilities of generating various options thereby optimizing the whole planning process. Change detection is an important part of monitoring and managing natural resources and urban development because it provides quantitative analysis of the spatial distribution of the population of interest (Gamanya et al. 2007).

2.1 Flood Inundation Mapping and Damage Assessment

Flooding induced by storm events is a major concern in many regions of the world (Townsend and Walsh 1998; Dutta et al. 2000; Sheng et al. 2001; Bryant and Rainey 2002; Horritt and Bates 2002; Hudson and Colditz 2003). Extreme weather in recent years has demonstrated the need for reliable flood models, as emergency managers and city planners begin to realize the importance of advance warning systems in severe storm situations (Knebl et al. 2005). As globally averaged temperatures increase, the potential for severe to extreme weather events increases (Becker and Grunewald 2003; WMO 2003). Therefore, global warming has brought further urgency to the prediction of flood levels and damages (Knebl et al. 2005). Flood inundation modelling requires distributed model predictions to inform major decisions relating to planning and insurance (Bates 2004). Since publication of the blueprint paper by Freeze and Harlan (1969), flood modelling has greatly improved in recent years with the advent of GIS, radar-based rainfall estimation using next generation radar (NEXRAD), high-resolution digital elevation models (DEMs), distributed hydrologic models, and delivery systems on the Internet (Garrote and Bras 1995; Bedient et al. 2003).

The Subernarekha River is one of the longest, rain-fed, inter-state rivers in the eastern parts of India. The river basin includes large areas of Jharkhand and some parts of West Bengal and Orissa. The basin lies between latitudes 21° 33′ N and 23° 32′ N and longitudes of 85° 09′ and 87° 27′ E. From 1960 to 2006, floods had occurred 14 times in the low-lying areas of Orissa on the banks of the Subernarekha River. For this reason, flood inundation problems of the Subernarekha River are of utmost important to the mining companies, state governments and local inhabitants. Figure 6.2 shows the study area with a buffer zone of 10 km around the Subernarekha River. This paper demonstrates applications of remote sensing and GIS applications of the Subernarekha River for assessing flood-affected areas. A good quality DEM has been prepared from CARTOSAT-1 stereo imageries. A total of 233 spot elevations were digitized from the contours of the DEM and verified

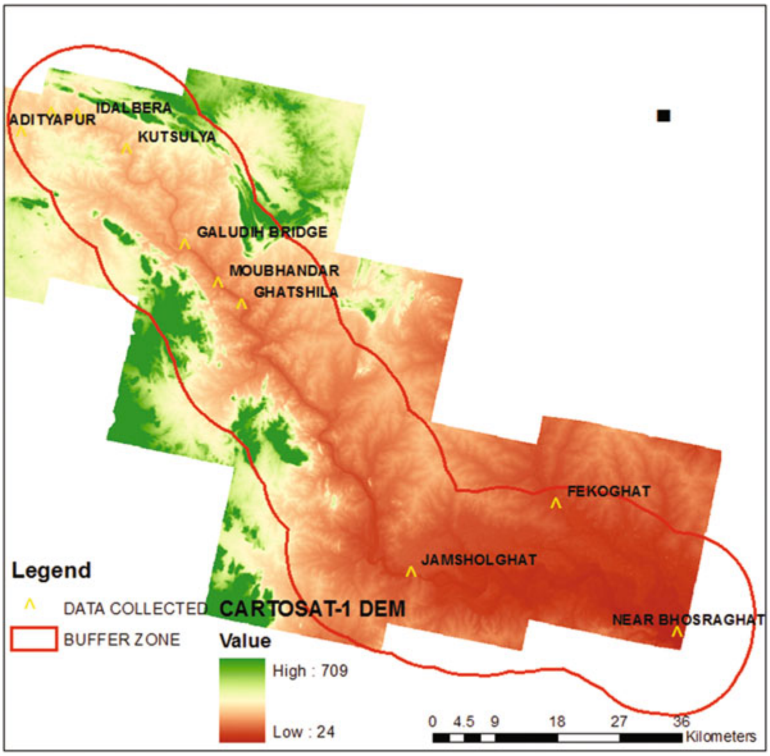


Fig. 6.2 DEM of the study area and a buffer zone of 10 km around the Subernarekha River

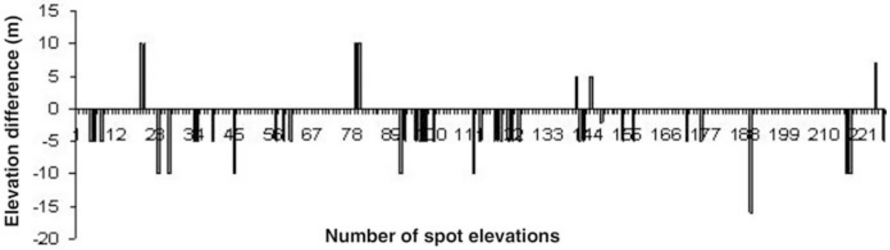


Fig. 6.3 Elevation difference between toposheet and DEM

with those of toposheets. A total of 239 cross sections have been extracted from the DEM and verified with those of measured cross-sections at various locations of the gauging stations in the study area. The calibration of hydrodynamic model for the year 1997 has been carried out. The performance of the hydrodynamic model has been assessed based on various error functions.

2.1.1 Digital Elevation Model (DEM) and Ortho-Image Generation

Ortho-image is an image that shows ground objects in their true map or orthographic projection. An orthographic projection is the one in which the projecting rays are perpendicular to the plane of projection. The digital terrain profiles generated in the ortho-photo production process comprise a DEM of the terrain covered by the ortho-photo. The procedure for making ortho-image are (i) interior orientation, (ii) exterior orientation, (iii) tie point generation, (iv) triangulation, (v) model refining using ground control points (GCPs), and (vi) DEM generation. For the development of digital elevation model (DEM) of the study area, a total of eight scenes have been procured from NRSC, Hyderabad. These eight scenes were mosaiced and a single image was generated for hydrodynamic modelling. The resolution of DEM was set at 25 m and the ortho-image had a spatial resolution of 2.5 m.

From this DEM, contours with 10 m interval were generated. For identifying the elevation errors in the DEM, these contours were cross-checked with toposheet contours. For this purpose 233 spot elevation points were digitized. The comparison of spot elevations is shown in Fig. 6.3. It can be seen that except at some locations, elevations estimated by DEM were in good agreement with the toposheets.

2.1.2 River Cross-Sections from DEM

River cross-sections are key inputs for hydrodynamic modelling of a river and its floodplain. The Subernarekha River has a length of about 154 km from Jamshedpur to Bhosraghat, and its elevation varies from 112.5 m (bed level at Jamshedpur) to

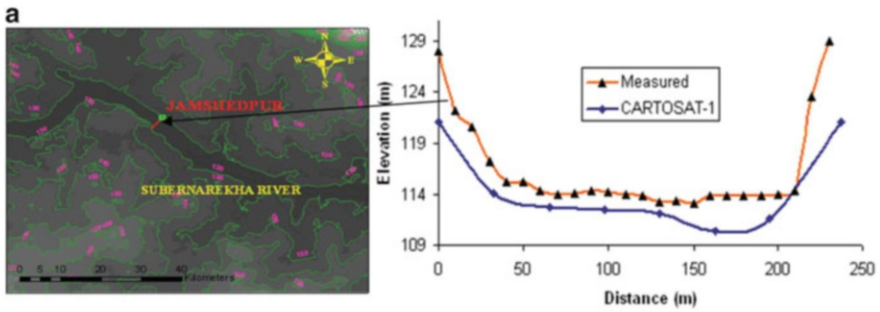


Fig. 6.4a Comparison of river profiles at Jamshedpur station

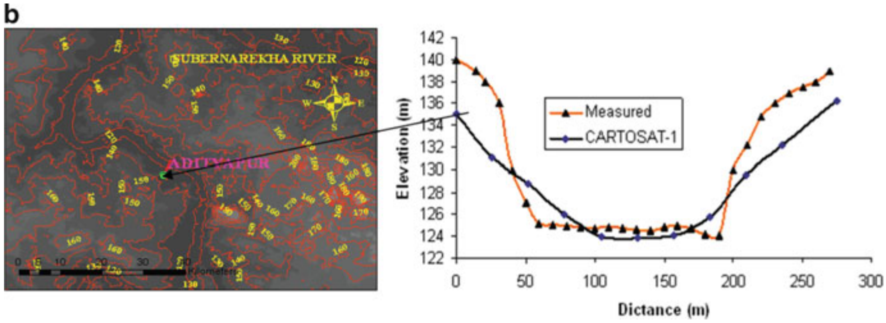


Fig. 6.4b Comparison of river profiles at Adityapur station

24.95 m (bed level near Bhosraghat). After preparation of a good quality DEM from CARTOSAT-1 stereo images, the cross-sections at various locations were extracted from Jamshedpur to Bhosraghat. A total of 239 cross-sections were extracted with an average interval of 644 m. Field survey was conducted from Ghatshila to Jamshedpur (40 km river length) for collection of cross-section data. A total of 15 cross-sections were collected from field survey. These cross-sections were compared with those of measured cross-sections. Comparisons of cross-sections across the Subernarekha River at different locations are shown in Figs. 6.4a, 6.4b, and 6.4c.

2.1.3 Hydrodynamic Modelling of the Subernareka River

Generation of water surface profiles was carried out using HEC-RAS software. Unsteady flow analysis was conducted along the Subernarekha River. Four gauging stations, viz., Jamshedpur, Ghatshila, Jamsholghat and Rajghat in the study area of the Subernarekha River are maintained by Central Water Commission (CWC) and data from these stations were available. The study area is restricted up to Bhosraghat. Hourly water level data near Bhosraghat were estimated using linear interpolation technique based on the data available at Rajghat and Jamsholghat.

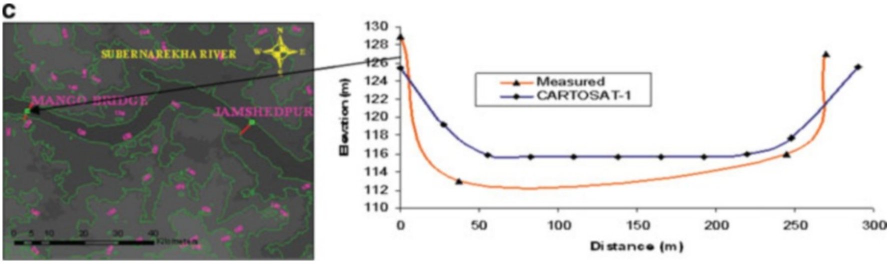


Fig. 6.4c Comparison of river profiles at Mango Bridge

Water level data at Bhosraghat gauging site was used as the lower boundary condition for hydrodynamic modeling. At the upstream section of the river, i.e., at Jamshedpur, the stage hydrograph was used as the upstream boundary condition.

2.1.4 Calibration of the Hydrodynamic Model

The hydrodynamic model was calibrated for the monsoon period starting from 16th June to 22nd September of 1997. In this study, for river banks and channel, Manning's roughness coefficient of 0.11 and 0.047 were found to be suitable. Comparison between measured and model discharge data at Jamshedpur and Ghatshila are shown in Figs. 6.5a and 6.5b. It can be seen that the model forecasts discharge fairly well. The index of agreement between the model and measured discharge varies from 0.89 to 1 and the percentage variation in peak ranges from –5.53 to 0.32. Map of the floodplain was also prepared in GIS and is shown in Fig. 6.6. It can be seen that major floods have occurred in the low-lying land of West Midnapore in West Bengal.

2.1.5 Damage Assessment

Assessment of damage due to flood is an integral part of flood inundation mapping. Figure 6.6 shows the floodplain map of the study area overlaid by the land use/land cover (LULC) map. Major floods have occurred in the plains of Medinapore district of West Bengal in 1997 and 2007. For assessing damages due to the flood in 1997, satellite imageries from IRS P6 with LISS III sensor having spatial resolution of 23.5 m were obtained. These images were used to classify the entire river basin into the following eight land use/land cover classes: (i) agriculture land, (ii) habitats, (iii) dense forest, (iv) mixed vegetation, (v) scrubs, (vi) plantation, (vii) water bodies, and (viii) barren land. Supervised classification technique with nearest neighbourhood algorithm is used for the classification of objects in the image. The classification was done using ERDAS IMAGINE 8.5.

This analysis indicates that in 1997, the flood affected areas comprising agriculture land, habitats, dense forest, mixed vegetation, scrubs, plantation, water bodies and barren land were 6228.38, 4663.69, 11.81, 1706, 181.38, 867.44, 94.19 and

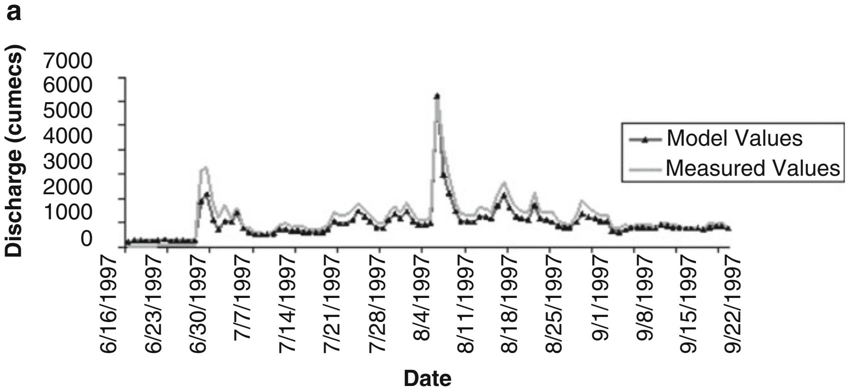


Fig. 6.5a The model and measured discharge values at Jamshedpur for the year 1997

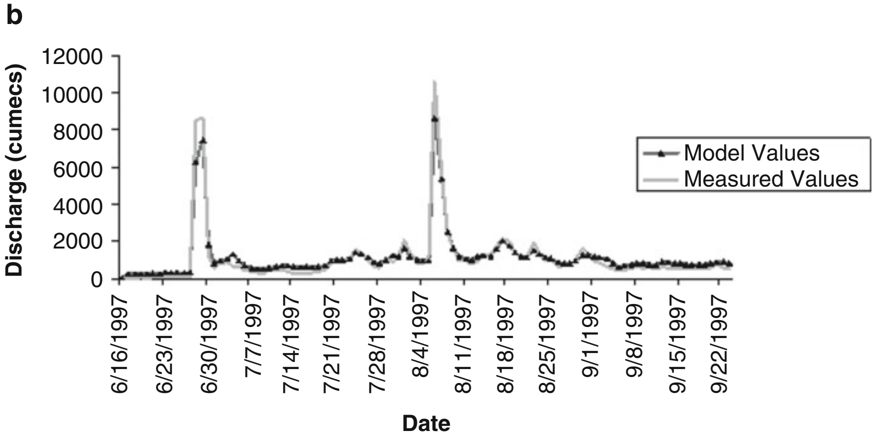


Fig. 6.5b The model and measured discharge at Ghatshila for the year 1997

120.88 hectares, respectively. The total flood affected area for the year 1997 was 13,873.75 ha. Since Medinapore district of West Bengal, India, has large areas of agriculture land near the Subernarekha River, it was the most affected area due to floods.

2.2 Detection of Land Pattern Changes in Korba Industrial Area

Mining is an anthropogenic activity which involves exploration and removal of minerals from the earth's crust. Mining activities may be associated with certain

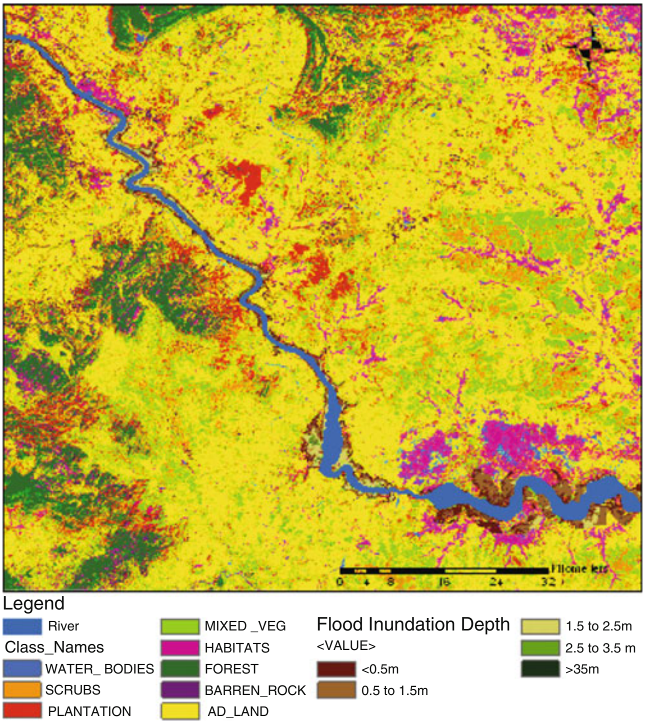


Fig. 6.6 Superimposition of flood inundation map and land use/land cover map

permanent and irreparable damage to the geo-environment. Its extent becomes unmanageable when mining is done in a haphazard manner and due care is not taken. Therefore it is essential to plan and monitor mining activities in order to develop mines in a sustainable way. For sustainable mine development, continuous monitoring, management and development of resources is necessary.

Monitoring of a mining operation involves numerous environmental and socio-economic considerations. Remote sensing and GIS can play an important role in monitoring anthropogenic activities like open-cast mining by providing synoptic and repetitive coverage of affected areas. Thus, identification and evaluation of geo-environmental degradation becomes techno-economically feasible and more convenient through applications of remote sensing. Recent advancement in sensor resolution, both spatial and spectral has helped in precise acquisition of spatio-temporal data. Similarly, GIS can handle huge amounts of spatial data on one convenient platform for spatial information retrieval and queries for decision-making. Collateral data related to mines, industries, and environmental quality data can be incorporated in the GIS platform along with data generated from remote sensing. GIS, thus, works as a spatial decision support system to managers for spatial planning in resource management and monitoring (Rajesh 2004). Remote Sensing and GIS can be integrated together to form a spatial information system, which can help mine managers and other executives in efficient spatial management and decision-making.

The study area lies in the south-eastern part of India at latitude 22° 20′ N and longitude 82° 42′ E (Survey of India, Toposheet No. 64 J/11. The total study area selected in this study is approximately 55,580.77 hectares as shown in Fig. 6.7. The area has great economic importance due to occurrence of 2000 million tonnes coal reserves up to a depth of 600 m (Singh and Dwivedi 1994), in addition to bauxite and granite minerals. Large surface coal mines, such as Gevra, Kusmunda, Dipka, Manikpur and many more which produce over 30 MT of coal every year lie along the river. Major power producing companies such as NTPC, CSEB, BALCO (BCPP) are located in this area with a total production capacity of more than 5560 MW. Due to high production capacity of these mines, land degradation in and around a coalfield is a major concern in this area. In surface or open-cast mining, the soil and rock strata overlying the mineral deposits are removed and relocated in order to reach the mineral deposit.

Korba region has been classified using 11 LULC classes. The class representing human settlements mingled with either barren land class or open shrubs class. The outputs of the classification of images of the study area of 1990, 1995, 1999 and 2004 are shown in Figs. 6.8a, 6.8b, 6.8c, and 6.8d respectively. Variations in land use/land cover classification of images over 14 years are presented in Fig. 6.9. It can be seen that dense forest area used to be 25% of the total study area in 1990 and was about 5% in 2004. On the other hand, vegetation area increased due to afforestation done by the mining companies.

2.3 Detection of Coal Fires in an Active Surface Coal Mine

Surface temperature in coal mining region is usually high due to dark coal and coal dust (black body effect) and coal fires. However, land surface over a mining area is characterized by diverse land cover types, including forest, agricultural lands, dumping area, water bodies, and exposed coal bed. Coal fires are difficult, persistent and costly problems throughout India.

Currently, available satellite thermal infrared sensors provide different spatial resolution and temporal coverage data that can be used to estimate land surface temperature as well as coal fire temperature. Thematic Mapper (TM) data are the most useful remotely sensed data for estimation of coal fire temperature (Gangopadhyay et al. 2006). TM data consist of seven bands; six of them are near visible and infrared region and one of them is in the thermal region.

TM1 (0.49 μm) is used for coastal water studies, TM2 (0.56 μm) is used for crop identification and vegetation studies, while TM3 (0.66 μm) and TM4 (0.83 μm) are used for calculation of vegetation indices such as NDVI (Normalized Difference Vegetation Indices) TNDVI. TM5 (1.65 μm) and TM7 (2.22 μm) are used for identifying cloud, ice, and geological formations.

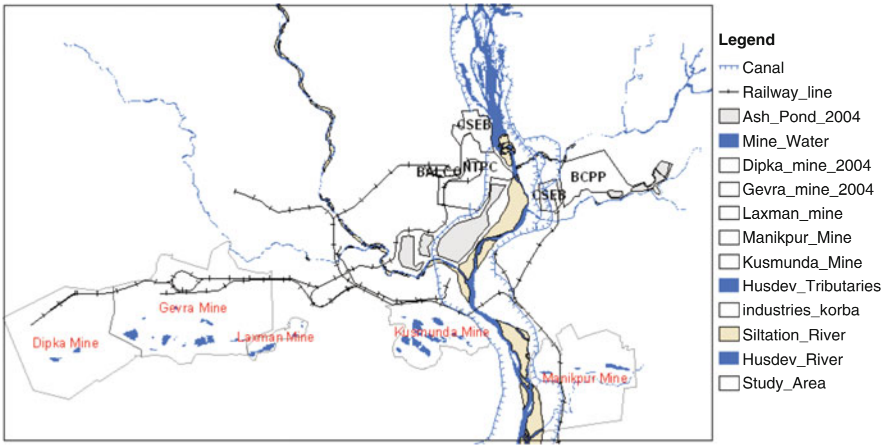


Fig. 6.7 Study area Korba coal field

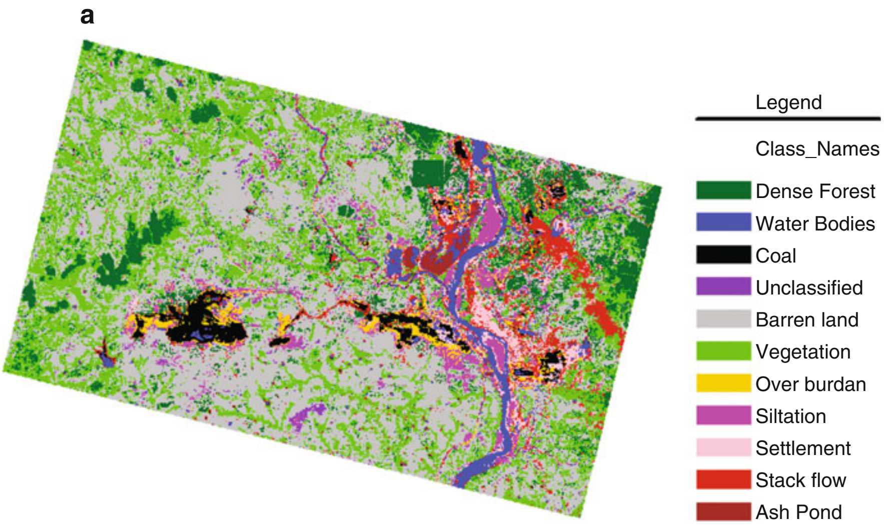


Fig. 6.8a LULC of the study area of year 1990

TM6 (11.457 μm) data can be used for retrieving information regarding coal fire temperatures. TM6 data provide information about radiant temperatures which are determined by temperature and the emissivity of the surface. The algorithm for coal fire determination is shown in Fig. 6.10. The main step in the algorithm is conversion of radiance from gain and bias of TM band. The radiance is directly proportional to gain and bias values of TM band data.

In India, coal fire temperature varies from 127 to 180 °C in Raniganj and Jharia coal fields. The Gevra mine temperature rises mainly in the summer season.

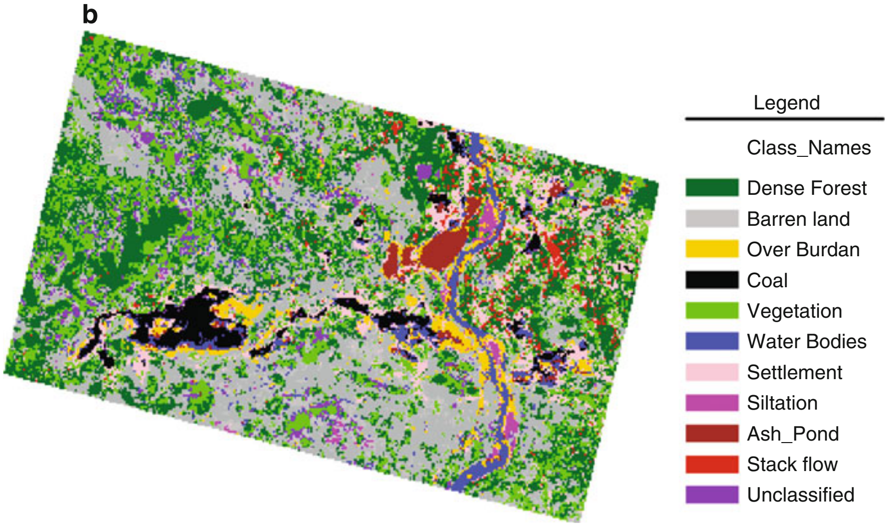


Fig. 6.8b LULC of the study area of year 1995

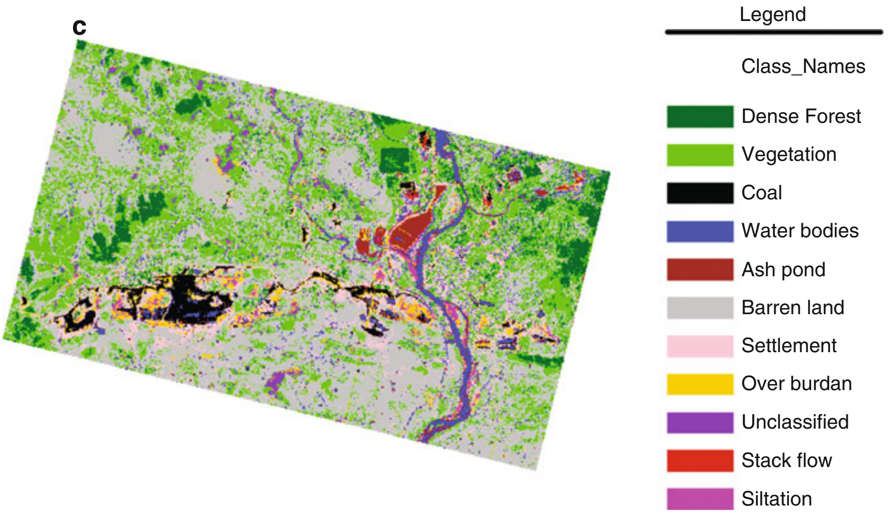


Fig. 6.8c LULC of the study area of year 1999

Figure 6.11 depicts snapshots of coal fires in Gevra mine. The entire mine and surrounding temperature rises in the summer season to the dry surrounding environment. Hence the coal gets fired easily.

Remote Sensing and GIS can be used for pre- or post-coal fire monitoring and detection (Prakash and Vekerdy 2004; Miller and Yool 2002). It is also helpful for

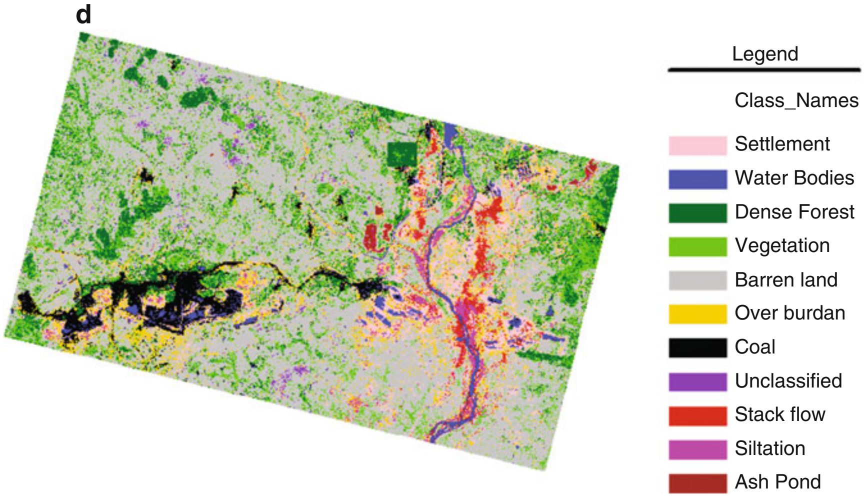


Fig. 6.8d LULC of the study area of year 2004

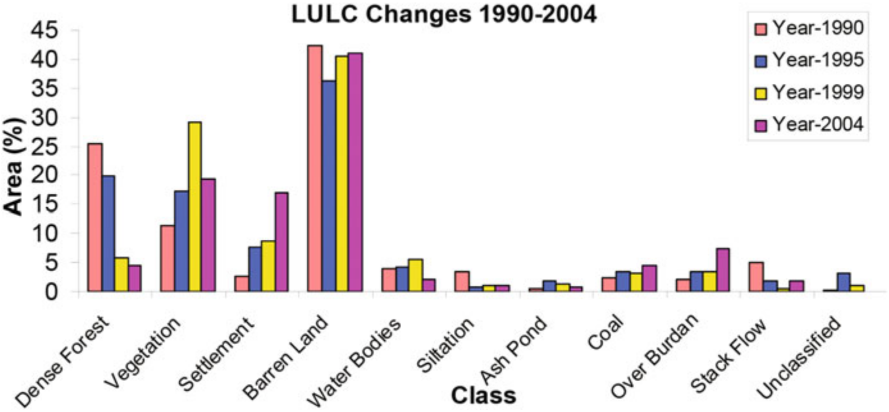


Fig. 6.9 Comparison of LULC of the study area

making decisions and for fire controlling measures. This technique is based on thermal remote sensing.

In this study, the coal fire temperature was detected from digital number (DN-Reflectance). Temperature of fire affected area was obtained by converting DN into spectral radiance and later radiance to temperature (Chander and Markham 2003). The temperature of the coal mine, i.e., any earth material can be obtained based on the thermal radiance which can be obtained from Planck's radiation equation (Eq. 6.2 below, Chatterjee 2006). Any reflected energy is related to wavelength. Higher the wavelength, lower will be the energy and vice versa. This reflected energy is sensed by different sensors based upon their applications. For the

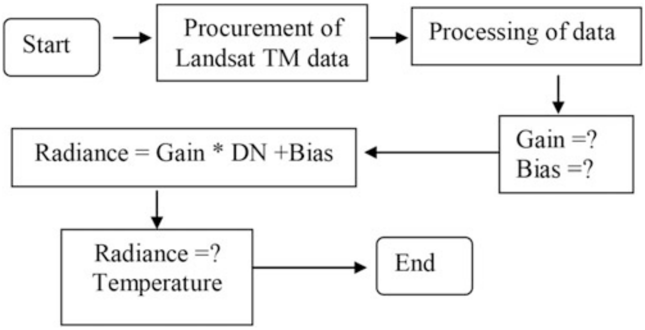


Fig. 6.10 Steps involved for coal fire determination of Gevra mine

Fig. 6.11 Coal fire affected areas of Gevra mine

temperature determination thermal sensors used namely Landsat TM (10.44–12.42 μm).

$$L_\lambda = \frac{2hc^2\lambda^{-5}}{e^{hc/\lambda kT} - 1} \tag{6.1}$$

where L_λ = Spectral radiance in W/m^2/sr/μm, λ = Wavelength in m, T = Radiant temperature of the object in °K, h = Planck's constant = 6.26×10^{-34} J s, c = speed of light = 3×10^8 m/s and k = Boltzmann constant = 1.381×10^{-23} J/K. Equation (6.1) can also be written as

$$T = \frac{{}^{hc}\!/_{\lambda k}}{\ln\left[\dfrac{2hc^2\lambda^{-5}}{L_\lambda} + 1\right]} \tag{6.2}$$

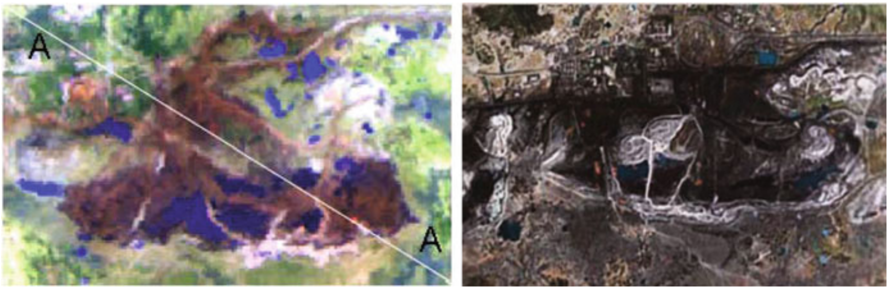


Fig. 6.12 Landsat TM FCC coal fire in Gevra Mine (1990 and 2000)

where

$$L_{\lambda} = \text{Gain}\ (\text{DN}) + \text{Bias} \tag{6.3}$$

With the help of header file (.hdr) the values of gain and bias has been obtained. The gain and bias can also be determined by Eq. (6.4).

$$\begin{aligned} &\text{Gain} = (L_{\text{MAX}} - L_{\text{MIN}})/255 \\ &\text{Bias} = L_{\text{MIN}} \end{aligned} \tag{6.4}$$

where L_{MAX} = Maximum radiance and L_{MIN} = Minimum radiance.

In this study, Landsat TM (Fig. 6.12) data has been used for calculating the surface temperature of Gevra coal mine.

Figure 6.13 indicates the correlation between digital numbers (DN) and temperature (Temp °C) along the path AA′. The peaks in Fig. 6.13 are indications of local fire zones along the specified line A-A′. These peaks were comparable to those found during ground validation of the local fires.

2.4 Thematic Mapping and Generation Queries from GIS Attribute Data

This case study area is located in the state of Jharkhand covering parts of East and Seraikhela Kharswan districts. The area comprises a total of 3000 km^2 including Bagjata, Jaduguda and Bandurang mines operated by Uranium Corporation of India Limited (UCIL). It can be noted that 6 out of 9 blocks of East Singhbhum district and 2 out of 8 blocks of Seraikhela-Kharsawan district are covered in the study area. The overall extent of the study area is presented in Fig. 6.14. The figure shows the study area along with the Subarnarekha River and Uranium mines. In this section, villages/urban areas, water bodies, mines, ground water, and forest diversity index mapping is presented. Apart from that query generation based on GIS database is also discussed in this section.

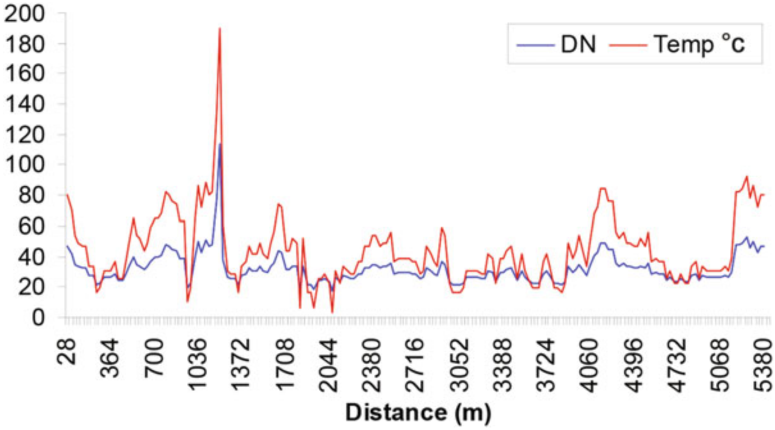


Fig. 6.13 Variation of surface temperature in Gevra mining area (A–A′ line)

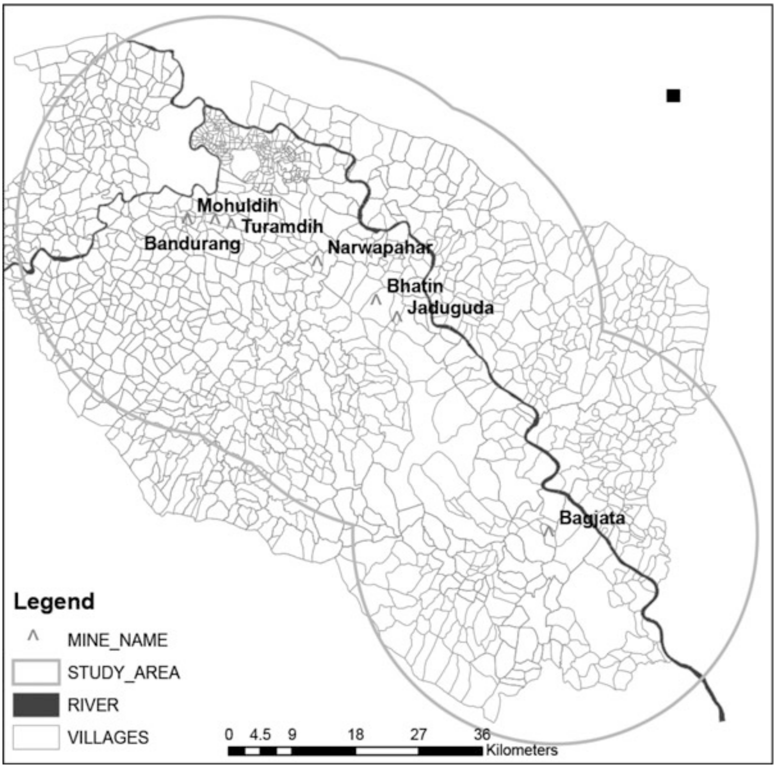


Fig. 6.14 Study area with villages and mines in River Subernarekha basin

2.4.1 Mapping of Villages/Urban Areas, Mines, Water Bodies

Figure 6.14 shows all villages (geo-referenced) along with important places, the Subernarekha River, the Kharkai River and mines in the study area. The information about any village can be obtained by clicking on the village map or by locating the attribute table of villages. Altogether 1261 number of villages was digitized in GIS environment. The attribute data were also collected from the BDO offices and subsequently attached with the individual villages. Cross-validation was done to remove all typographical errors. The queries and report of villages can also be generated based on the data (attributes) attached with villages. Village attributes are same as administrative blocks as given below: male, female, total population, SC-ST populations, children population, literacy rates and others.

2.4.2 Mapping of Ground Water in a Mining Area

Groundwater information pertaining to the ground water level below the surface was provided by UCIL. This information includes the location, collar RL and ground water level below the surface of the 15 wells in and around of Bandurang and Turamdih mines. Using this well information, ground water mapping in the areas of Bandurang and Turamdih mines was carried out by the inverse squared distance interpolation technique for the data of 2008.

Figures 6.15a and 6.15b present contour plots of surface profile, groundwater profile with respect to surface (below surface) and groundwater profile with respect to the datum (WGS-84). Figure 6.15a presents the location of groundwater wells along with local streams. From this figure, general topography of the area can be ascertained. Water head above the datum is plotted in Fig. 6.15b and it can be inferred that the general groundwater flow directions are towards north-west (towards the Kharkai River) and south-east (towards the Subernarekha River).

2.4.3 Mapping of Forest Diversity Index

Diversity index is a mathematical measure of species diversity in a community. Diversity indices provide more information about community composition than simply species richness (i.e., the number of species present); they also take the relative abundances of different species into account. The data related to forest diversity index is obtained from the PC, BARC. Figures 6.16a and 6.16b show the Forest Diversity Index around the Bandurang and Bagjata mining area respectively.

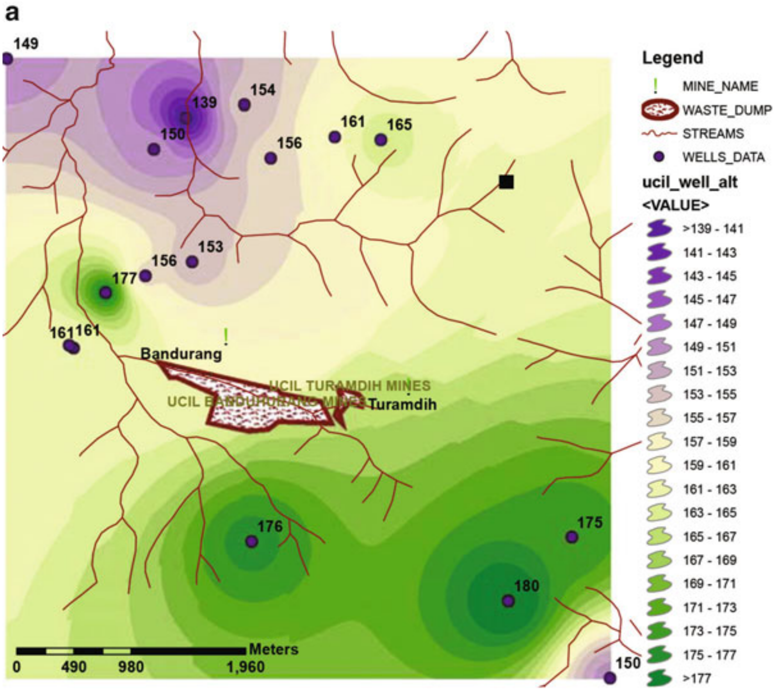


Fig. 6.15a Contour plots of altitude of groundwater wells (values in m)

2.5 *Query Generation Based on GIS Database*

One of the significant tools of GIS is to generate queries based on the attribute data. In GIS generation of queries can be done in two ways: (i) spatial queries, and (ii) attribute queries. Figure 6.17 shows map that is generated based on the GIS attribute data as given below.

The query statement is 'find the villages those belong to':

Population Density (persons/sq. m^2) $>$ 200 and *Female to Male Ratio* $>$ 2

3 Conclusions

Applications of RS and GIS in retrieving, assimilating, storing, and analyzing various environmental data are presented in this chapter. Image processing techniques and GIS applications in various research areas are also mentioned. Four case studies are elaborated to show the efficacy of RS and GIS techniques in modeling river runoff, land use/land cover changes, coal fire detection and thematic mapping using GIS data. Preparation of DEM from CARTOSAT-1 images for flood plain of

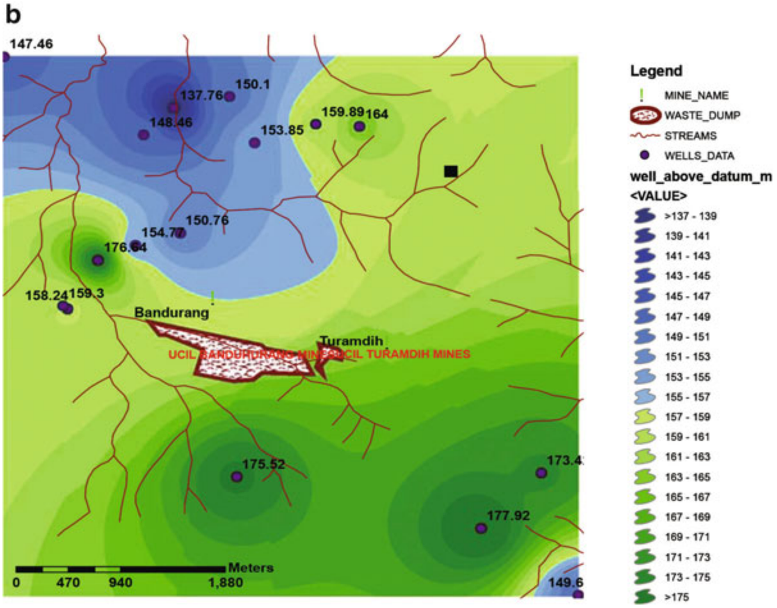


Fig. 6.15b Contour plot of groundwater profile with respect to the datum (values in m)

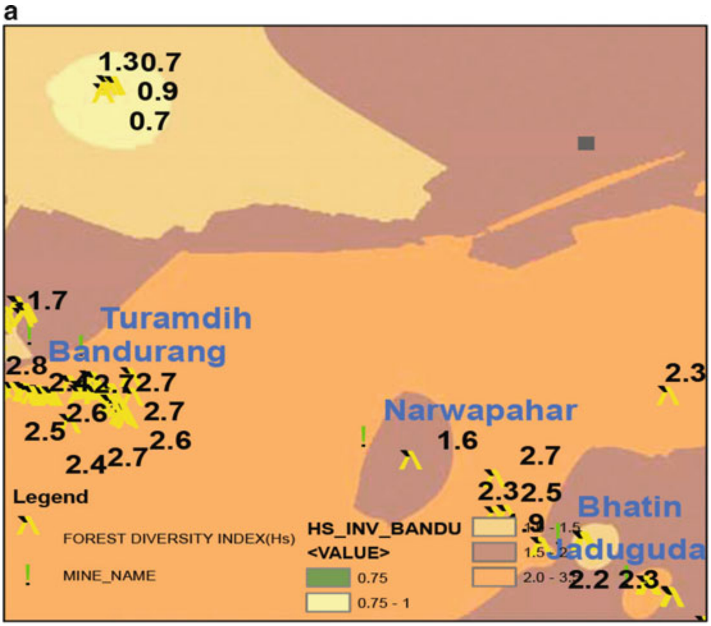


Fig. 6.16a Forest diversity index around the Bandurang mine

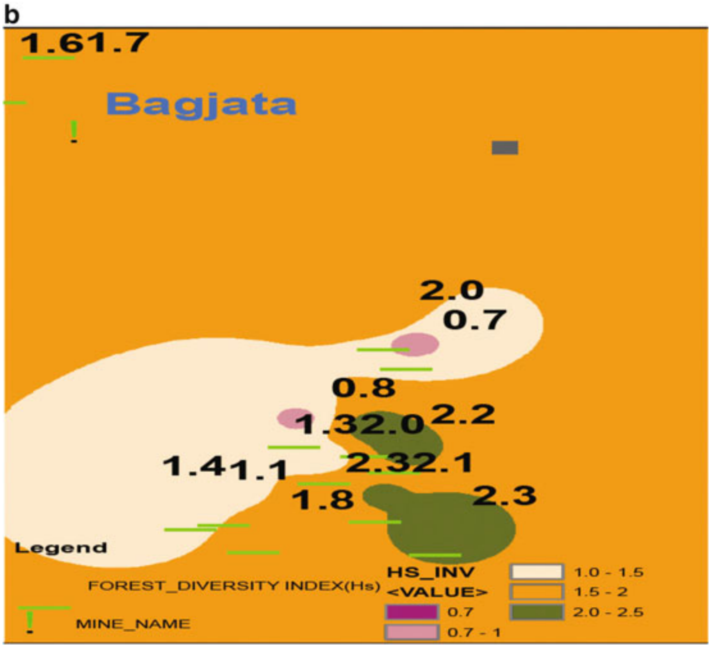


Fig. 6.16b Forest diversity index around the Bagjata mine

the Subernarekha River has been carried out to extract 239 cross-sections for hydrodynamic modelling of river runoff. Flood inundation mapping and damage assessment due to flood for the year 1997 has also been determined and found that low-lying area of West Midnapore district, West Bengal is affected due to flood. The study finds that flood affected areas under agriculture land, habitats, dense forest, mixed vegetation, scrubs, plantation, water bodies and barren land were 6228.38, 4663.69, 11.81, 1706, 181.38, 867.44, 94.19, and 120.88 hectares, respectively.

LULC change study of Korba industrial area show that area of dense forest has reduced from 25% to less than 5% of the total area between the year 1990 and 2004. During the same years, the settlement growth has occurred from 2 to 16%, which indicates increase in population in the study area due to various industrial activities.

The maximum temperature of Gevra coal mine fire was obtained as 190°C while average mine temperature was found to be around 30–45 °C. Application of GIS and thematic mapping for presentation of groundwater levels, forest diversity index, and villages/urban areas in the East Singhbhum area has also been shown on a GIS platform.

Acknowledgements The authors thank Central Water Commission (CWC) for providing the necessary data. The authors also thank Board of Research in Nuclear Sciences (BRNS) and Space Application Center (SAC), Ahmedabad for sponsoring these projects. The authors express their

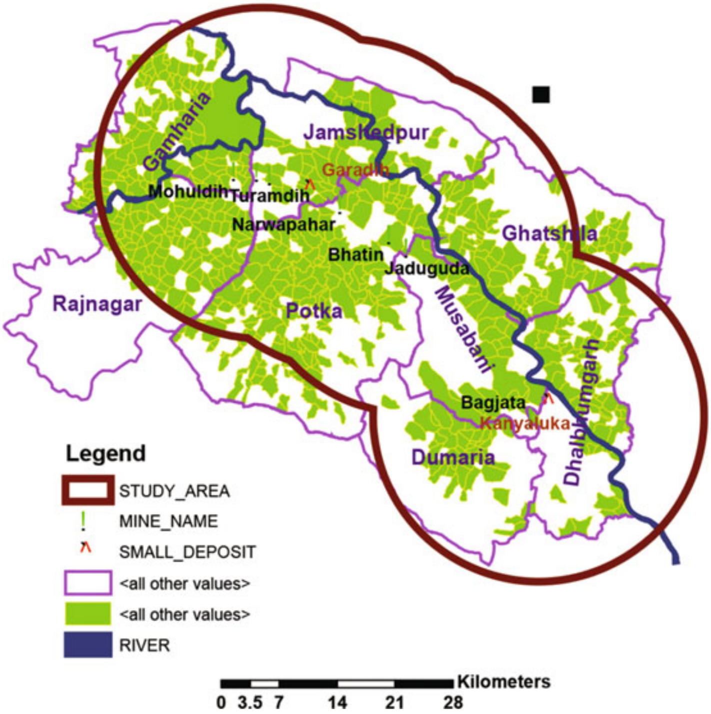


Fig. 6.17 Village-wise query on population density

deep gratitude to Uranium Corporation of India Limited (UCIL) for sharing valuable information and providing constant support for this research work

References

Bates, P.D., 2004. Remote sensing and flood inundation modeling. *Hydrological Processes*, **18**, 2593–2597.

Bedient, P.B., Holder, A., Benavides, J.A. and Vieux, B.E., 2003. Radar-based flood warning system applied to tropical storm Allison. *Journal of Hydrologic Engineering*, **8(6)**, 308–318.

Belward, A.S. and Valenzuela, C.R., 1990. Remote Sensing and Geographical Information Systems for Recourse Management in Developing Countries. Kluwer Academic Publisher, London.

Becker, A. and Grunewald, U., 2003. Flood risk in central Europe. *Science*, **300(5622)**, 1099.

Bryant, R.G. and Rainey, M.P., 2002. Investigation of flood inundation on playas within the Zone of Chotts, using a time-series of AVHRR. *Remote Sensing of Environment*, **82(2/3)**, 360–375.

Chander, G. and Markham, B., 2003. Revised Landsat-5 TM Radiometric Calibration Procedures and Postcalibration Dynamic Ranges. *IEEE Transactions on Geosciences and Remote Sensing*, **41**, 11.

Chatterjee, R.S., 2006. Coal Fire Mapping From Satellite Thermal IR Data – A Case Example in Jharia Coalfield, Jharkhand, India. *ISPRS Journal of Photogrammetry & Remote Sensing*, **60**, 113–128.

Dutta, D., Herath, S. and Musiake, K., 2000. Flood inundation simulation in a river basin using a physically based distributed hydrologic model. *Hydrological Processes*, **14(3)**, 497–519.

Freeze, R.A. and Harlan, R.L., 1969. Blue-print for a physically-based digitally simulated hydrologic response model. *Journal of Hydrology*, **9**, 237–258.

Gangopadhyay, P.K., Dutt, K.L. and Saha, K., 2006. Application of remote sensing to identify coalfires in the Raniganj Coalbelt, India. *International Journal of Applied Earth Observation and Geoinformation*, **8**, 188–195.

Garrote, L. and Bras, R.L., 1995. A distributed model for real-time flood forecasting using digital elevation models. *Journal of Hydrology*, **167**, 279–306.

Gamanya R., Maeyer, P.D. and Dapper, M.D., 2007. Object-oriented change detection for the city of Harare, Zimbabwe. *Expert Systems with Applications*, **36**, 571–588.

Horritt, M.S. and Bates, P.D., 2002. Evaluation of 1D and 2D numerical models for predicting river flood inundation. *Journal of Hydrology*, **268(1–4)**, 87–99.

Hudson, P.F. and Colditz, R.R., 2003. Flood delineation in a large and complex alluvial valley, lower Panuco basin, Mexico. *Journal of Hydrology*, **280**, 229–245.

Knebl, M.R., Yanga, Z.L., Hutchison, K. and Maidment, D.R., 2005. Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: A case study for the San Antonio River Basin Summer 2002 storm event. *Journal of Environmental Management*, **75**, 325–336.

Lillesand, T.M., Kiefer, R.W. and Chipman, J.W., 2004. Remote Sensing and Image Interpretation. John Wiley, Singapore.

Miller, J.D. and Yool, S.R., 2002. Mapping Forest Post Fire Canopy Consumption in Several Overstory Types Using Multi-Temporal Landsat TM And ETM Data. *Remote Sensing of Environment*, **82**, 481–496.

Prakash, A. and Vekerdy, Z., 2004. Design and Implementation of a Dedicated Prototype GIS for Coal Fire Investigation in North China. *International Journal of Coal Geology*, **59**, 107–119.

Rajesh, H.M., 2004. Application of Remote Sensing and GIS in Mineral Resource Mapping –An Overview. *Journal of Mineralogical and Petrological Sciences*, **99**, 83–103.

Roy, P.S., Subudhi, A.P. and Sokhi, B.S., 2001. Remote Sensing and GIS Application in Urban and Regional Studies. Human Settlement Analysis Group, IIRS, Dept. of Space, GOI, Dehradun, India.

Singh, R.M. and Dwivedi, C.S., 1994. A Study of Coal Facies in the Korba Sub-basin, Mahanandi Valley, India. *International Journal of Coal Geology*, **25**, 113–132.

Sheng, Y., Gong, P. and Xiao, Q., 2001. Quantitative dynamic flood monitoring with NOAA AVHRR. *International Journal of Remote Sensing*, **22(9)**, 1709–1724.

Townsend, P.A. and Walsh, S.J., 1998. Modeling floodplain inundation using an integrated GIS with radar and optical remote sensing. *Geomorphology*, **21(3/4)**, 295–312.

WMO (World Meteorological Organization), 2003. Our Future Climate (Publication WO-952).

Chapter 7
Applications of Remote Sensing and GIS in Solid Waste Management – A Review

Deblina Dutta and Sudha Goel

1 Introduction

Solid waste, thrown away in our surroundings and heaped on Mother Earth every day, is a by-product of civilization. Waste has irritated civilization for thousands of years. With rapid growth in world population, industrial revolution and greater consumerism, the amount of waste generated has grown exponentially. Thus, both economic development and population increase have contributed to the rising volumes of waste. In the last few decades, with greater ease in the movement of money, goods and population, generation and consumption of goods has increased resulting in increased production of waste materials. Generation of wastes is an indication of inefficient use of resources, making products less valuable. From a scientific viewpoint, waste management requires consideration of the waste and the type of place where the waste has originated.

1.1 Why Is It Important to Manage Waste?

Waste-related problems have both temporal and spatial aspects. One of the reasons for regulating waste treatment and disposal is that wastes have substantial negative impacts on society and the environment. Public health and the integrity of

---

D. Dutta (✉)
School of Environmental Science and Engineering, Indian Institute of Technology Kharagpur,
Kharagpur 721302, West Bengal, India
e-mail: deblina69envs@gmail.com

S. Goel
Civil Engineering Department, Indian Institute of Technology Kharagpur,
Kharagpur 721302, WB, India

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_7

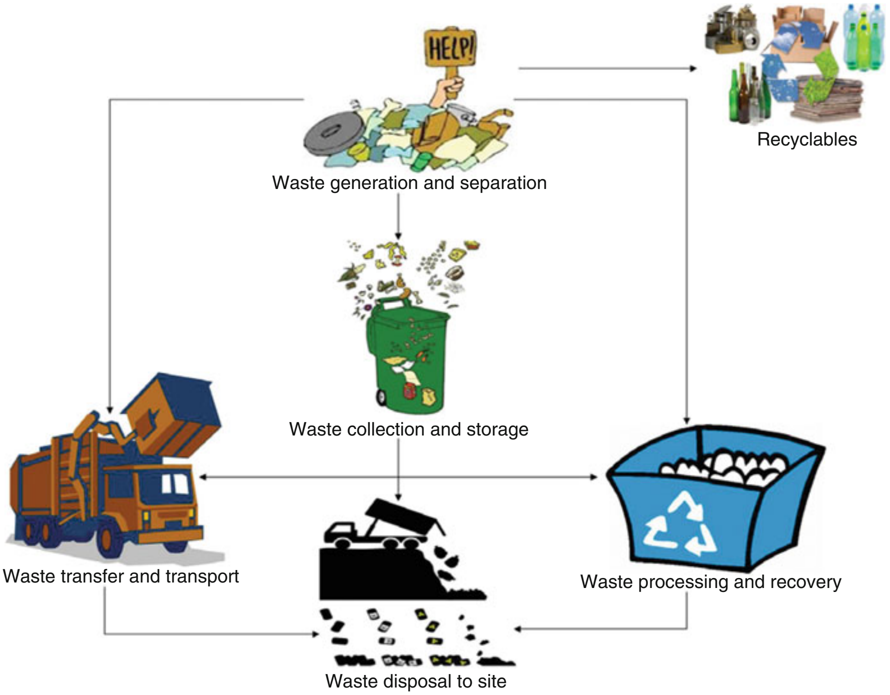


Fig. 7.1 Activities involved in solid waste management

ecosystems are affected by the waste; it can hamper our aesthetic sensibilities and economics. So we need proper waste management to control diverse types of pollution, i.e., air, soil and water pollution, to stop the spread of communicable diseases; to conserve all our environmental resources, including forests, minerals and water and for recycling of resources for additional production. Management and recycling of wastes are not new concepts or activities. Problems related to solid waste management in today's world are complex because of the diverse sources, increasing quantities and varying composition of the wastes. Many activities are included in solid waste management from its generation till its final disposal. The activities involved can be grouped into six functional elements (Fig. 7.1): (1) Waste generation and separation at source, (2) Recycle and reuse (3) Collection and storage, (4) Transfer and transport, (5) Processing and recovery, and (6) Disposal.

The objective of solid waste management is to ensure that air, soil and water pollution is reduced or eliminated and the waste is reused or recycled to the maximum possible extent. Solid Waste (Management and Handling) Rules, 2000 were promulgated for managing solid waste appropriately and have assigned the responsibility for municipal waste management to urban local bodies (ULBs). The present ad hoc approach to MSW collection and transport results in inefficient utilization of resources. For the development of solid waste management systems, various types of policies and technologies have been implemented such as: waste prevention at the generation point, reuse and recycling, composting, incineration and sanitary landfilling. Innovative technologies are being used and tools like Remote Sensing (RS), Geographic Information System (GIS) and mathematical optimization methods can be used for allocation and utilization of resources efficiently (Goel 2008). RS is used for sensing the earth surface, its environment and its resources without being in physical contact with it. RS can provide a synoptic view of a large area with capacity of repetitive coverage (Nishant et al. 2010). GIS can be used for collecting, storing and recovering spatial data which can then be transformed, analyzed and displayed for various applications. GIS are being used in solid waste management because the relationships between resources in term of spatial attributes and their planning and operations can be managed efficiently. GIS deals with the time and cost of solid waste management in each step and allows evaluation and implementation of best management practices with various alternatives. The objective of this review is to summarize applications of GIS and RS to Municipal Solid Waste Management (MSWM). Studies from abroad are summarized in Table 7.1 and those from India are summarized in Table 7.2.

2 The Role of RS and GIS in Sustainable Solid Waste Management

GIS can be combined with Global Positioning System (GPS) and Remote Sensing (RS) in recording spatial data and directly using the data for analysis and cartographic representation (Chalkias and Lasaridi 2009). GIS has proved to be very helpful in reducing time and is also very cost-effective. GIS has applications in various fields like urban planning, transportation, protection and management of natural resources, forestry, natural disaster management, health services, environmental modelling and engineering (Brimicombe 2003). Besides these, GIS has been used successfully for various applications in solid waste management. GIS can be used in every step in the process, i.e., from cradle to grave of the waste (especially hazardous waste) or from generation to disposal. The most common applications of GIS in SWM are siting waste management and disposal facilities and optimizing Waste Collection and Transport (WC&T) (Ghose et al. 2006). Moreover, GIS has been used effectively for locating recycling drop-off centres (Chang et al. 1997), optimising solid waste management in coastal areas, estimation of solid waste generation rates taking into account local demographic and socioeconomic data (Vijay et al. 2008). Using RS in conjunction with GIS allows decision makers to optimize MSWM by improving its efficiency and increasing economic returns or savings.

Table 7.1 Applications of remote sensing and GIS in solid waste management: International scenario

Sl. No	Techniques	Area of application	Study location	References
1.	ARC/INFO GIS program, operating on a SUN SPARC workstation	Vehicle routing and scheduling for solid waste management systems	Taiwan	Chang et al. (1997)
2.	Multi-criteria evaluation methods combined with GIS	Suitability for landfill	Giroft city in Kerman province of Iran	Javaheri et al. (2006)
3.	GIS and RS techniques	Suitable areas for waste disposal	Niamey, Niger Republic	Twumasi et al. (2007)
4.	Computer as a tool	Selection of landfills	Nigeria cities	Agaji and Wajiga (2007)
5.	Analytic network process (ANP) combination of GIS and a multi-criteria decision making method (MCDM)	Siting of landfill	Damaturu town, Nigeria	Babalola and Busu (2011)
6.	GIS, RS techniques and multi-criteria analysis methods	Suitable solid waste dumping sites	Bahir Dar Town, Ethiopia	Ebistu and Minale (2013)
7.	Hybrid method between Chaotic Particle Swarm Optimization and Arc GIS	Municipal solid waste collection	Danang city, Vietnam	Son (2014)
8.	GIS ARCView	Solid waste collection routes optimization	Ipoh city, Malaysia	Malakahmad et al. (2014)
9.	Suitability Index through GIS	Suitability for landfill placement	Prahova County, Romania	Mănoiu et al. (2013)
10.	RS and GIS	Waste disposal and management	Ondo State, Nigeria	Oyinloye (2013)
11.	RS and GIS	Selection of dumpsites and transport routes	Abeokuta, Nigeria	Adeofun et al. (2011)
12.	GIS and Analytical Hierarchy Process (AHP)	Disposal site selection	Senirkent–Uluborlu (Isparta) Basin, Turkey	Şener et al. (2011)
13.	ArcGIS, GPS and satellite imagery	Solid waste management	Niger State, Nigeria	Sule et al. (2014)
14.	GIS	Evaluation of landfill site	Ahvaz City, Iran	Davami et al. (2014)
15.	GIS	Solid waste disposal management system	Nigeria	Idowu et al. (2012)
16.	GIS and semi-quantitative risk assessment	Selection of disposal site	Kandy District, Sri Lanka	Balasooriya et al. (2014)
17.	GIS	Decision support tool	Nairobi, Kenya	Muriithi and Mutua (2012)

Table 7.2 Applications of remote sensing and GIS in solid waste management: National scenario

Sl. No	Techniques	Area of application	Study location	References
1.	Multi-objective decision making approach	Waste collection system	Tamil Nadu (Chennai)	Sudhir et al. (1996)
2.	GIS based decision support system, MCE models: AHP, FIC, ANN and Delphi	Landfill site selection	Tamil Nadu (Chennai)	Natesan and Suresh (2002)
3.	ArcGIS platform	Data management, validation and analysis module. Through these modules transfer station capacity, site sensitive index (SSI) and suitable site for landfill were selected	Medak (Andhra Pradesh)	Reddy (2005)
4.	Route planning using GIS	Collection and transport route planning	Asansol (West Bengal)	Ghose et al. (2006)
5.	RS and GIS, DSS	Disposal site selection	Hyderabad (Andhra Pradesh)	Padmaja et al. (2006)
6.	GIS based DSS (Decision Support System)	Optimal route analysis for transportation of waste	Hyderabad (Andhra Pradesh)	Reddy and Padmaja (2007)
7.	Multi-criteria mixed integer linear programming model	Location-allocation problem	–	Erham et al. (2008)
8.	MCDA (Multi- Criteria Decision Analysis), Analytical Hierarchy Process, ArcGIS	Dumpsite selection	Pondicherry (India)	Sumathi et al. (2008)
9.	ArcGIS and NET Engine programming tools	Estimation of waste generation, onsite operation, primary collection, transportation, resource recovery and disposal	Varanasi city (Uttar Pradesh)	Ohri and Singh (2010)
10.	Sustainability based decision support system	Composting	Sahibzada Ajit Singh Nagar (Punjab)	John (2010)
11.	GIS based collection and transportation model	Optimal route map	Pallavapuram	Kanchanabhan et al. (2010)
12.	Satellite data and linear regression analysis	Characterize solid waste and generate coefficient for estimating quantity of waste components	Nagpur (Maharashtra)	Katpatal and Rao (2011)
13.	Arc GIS 8.3	Routing and location of dumping site	Kottayam	Nishant et al. (2010)
14.	Arc GIS tools, DSS	Sustainable municipal solid waste management,		Saxena et al. (2010)

(continued)

Table 7.2 (continued)

Sl. No	Techniques	Area of application	Study location	References
		technological, institutional and financial aspects	Allahabad city (Uttar Pradesh)	
15.	Optimal routing model and decision support tool and characterization of municipal solid waste	Optimization of routing system	Chandigarh	Khajuria et al. (2011)
16.	Consider constraint, Spatial analysis tool of Arc GIS	Dumpsite selection	Allahabad city (Uttar Pradesh)	Saxena and Srivastava (2011)
17.	Combining GIS with Analytical Hierarchy Process (AHP), GPS	Waste disposal site selection	Mysore city	Basavarajappa et al. (2012)
18.	Arc Map GIS through Spatial Analysis Extension and weightage for the principal criteria	Waste dumpsite selection	Dharmanagar Town (Tripura)	Choudhury and Das (2012)
19.	ArcGIS, criteria map based on constraint and factor map	Landfill site selection	Roorkee (Uttarakhand)	Shukla et al. (2012)
20.	ERDAS Imagine 9.1 and Arc-GIS 9.2. Through network dataset preparation and network analyst tool utilization optimized route selected	Route optimization	Chandrapur Town (Maharashtra)	Siddam et al. (2012)
21.	Arc GIS	Location of bins	Sidhapudur ward, Coimbatore (Tamil Nadu)	Nithya et al. (2012)
22.	SPSS16 software, weighted mean centre (WMC) for extraction of alternate location of dust bin	Bin placement and settlement map.	Kumbakonam Town (Tamil Nadu)	Senthil et al. (2012)
23.	Application of analytical hierarchy process and spatial analyst tool	Suitable landfill site selection	National Capital Territory (Delhi)	Kumar and Hassan (2013)
24.	Arc/Info GIS and GPS	Bin placement and route optimization model	Singanallur ward of Coimbatore (Tamil Nadu)	Velumani (2014)
25.	Analysis by Arc GIS and natural break classifier for classification of population, waste generation	Population density and waste generation estimation	Coimbatore (Tamil Nadu)	Shoba and Rasappan (2013)

(continued)

Table 7.2 (continued)

Sl. No	Techniques	Area of application	Study location	References
	and distribution of ward workers			
26.	Suggest Arc GIS	Suggest criteria and methodology for landfill site selection	–	Khan and Samadder (2014)

3 Applications of Remote Sensing and GIS in Solid Waste Management

3.1 Generation of Solid Waste

With rapid urbanization and constant growth in population there has been a drastic increase in solid waste generation. The composition and generation of solid waste is influenced by several factors like physical, geographical, socio-cultural, economic and political. According to a study by Central Pollution Control Board (CPCB), about 47 million tons of solid waste is generated in India every year which is approximately 1.3 lakhs tons every day. In the next fifteen years, the waste generation rate is expected to increase between 1.2 and 1.4 kg/day-person (Hoornweg and Bhada-Tata 2012). Each municipality generally conducts a waste generation survey to estimate the total volume and weight of solid waste in their region. The ground-based analysis estimates the inter-relationship between the above parameters and the waste generation and composition in different areas (Karadimas and Loumos 2008). Waste characterization is also important because it involves analysis of the anticipated solid waste. Solid wastes contain a variety of substances which require different processes for handling and recycling. Nowadays in several places, different colour-coded bins like blue for recyclable wastes, green for organic and red for toxic wastes are being used for waste separation at the source.

In recent years, managing the huge amounts of solid waste generated has become a major concern, and in this regard, GIS has proved to be a boon for planners. Population distribution data and data for the amount of solid waste generated in a particular area are collected and different layers of population and solid waste data are created in GIS. Then all the layers are stacked (or superimposed) above the study area for subsequent analysis. Analysis of layers can be done, and areas with increased solid waste generation can be identified, classified into different categories and proper measures can be applied. Thus, RS and GIS can be used for the identification and classification of areas based on solid waste generation rates and identification of sites for disposal of solid waste.

3.2 Temporary Storage of Waste

Temporary storage of solid waste after generation and proper segregation is an important part of an efficient SWM plan. For waste storage, appropriate placement of bins on the road is very important. The placement of bins should be done properly so that collection and transportation become easier. Different GIS techniques have been applied for the placement of bins in an area with an efficient transportation system. According to Indian guidelines (CPHEEO), the spacing between bins should not be more than 500 m and the maximum distance between generation and collection points, i.e., households and bin should be 250 m (Liebman et al. 1975). Environmental System Research Institute (ESRI 1994) Arc/Info programme can be used for such analysis. Detailed information is required for planning and managing the system and includes the following (Vijay et al. 2008):

- Base map
- Road network
- Road elevation survey data
- Information of road class

Thematic maps and attribute data are included in GIS and computations are run through GIS-based Arc Macro Language (AML) algorithm (ESRI 1992).

Figure 7.2 illustrates the process of defining optimal locations for storage bins based on the topography and road network analysis. Phase 1 includes preparation of thematic maps with digitization, building coverage, and compiling of databases. Phase 2 includes computation of GIS-based programmes for optimizing location and number of bins in the service area (Vijay et al. 2008). Settlement maps showing linear, cluster or nucleus type of settlements can be prepared in ARC-GIS and the total waste generated from that area can be measured. Using the software SPSS 16, coordinates and the settlement data, Weighted Mean Centre (WMC) has been employed to extract alternative locations of dust bins (Deswal and Laura 2014).

3.3 Solid Waste Collection and Routing Efficiency

Waste collection and transportation (WC&T) comprise approximately 80–90% of the overall SWM budgets in low-income countries while collection efficiencies remain below 50%. In contrast, collection efficiencies are greater than 90% in high-income countries and collection costs are $<10\%$ of the total SWM budgets (Hoornweg and Bhada-Tata 2012). Therefore, optimization of collection routes

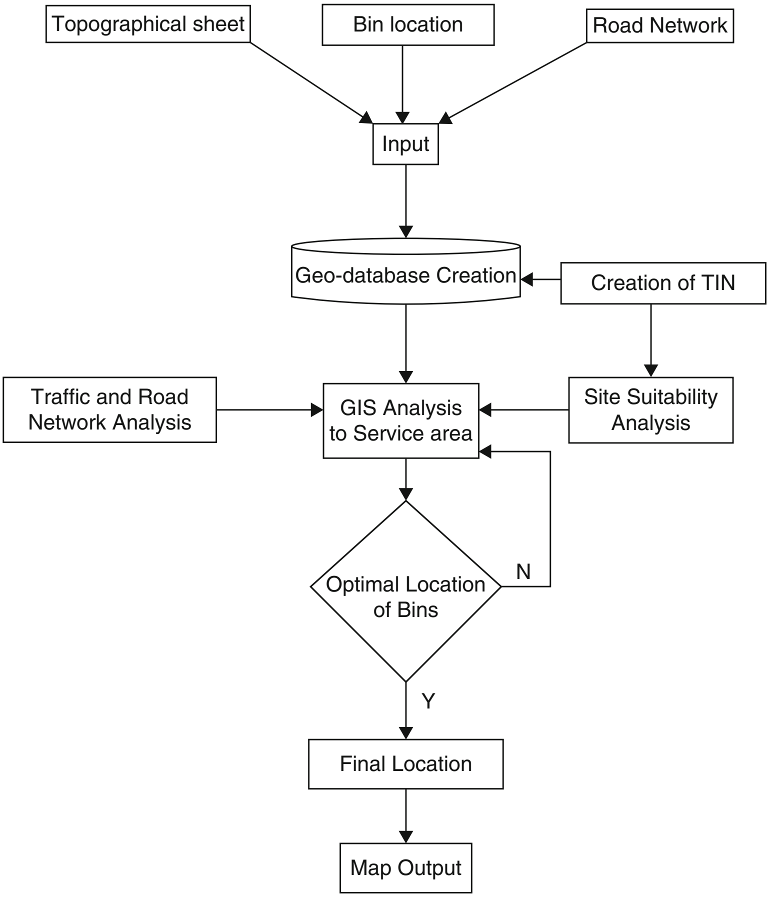


Fig. 7.2 Flowchart for defining optimal locations of storage bins. (*TIN* triangular irregular network)

and bin locations is a critical need in low-income countries. Some of the problems faced during waste collection are:

- Change in waste generation rates over time
- Large service areas
- Transportation
- Labour expenses
- Lack of proper planning.

GIS was used to delineate optimal routes for collecting solid waste by using network analysis. Initially, collection of all ancillary data was done from various sources (Bhambulkar 2011). Then the NETWORK module (ESRI 1995) of Arc/Info GIS software was used to provide network-based spatial analysis which includes routing, travelling directions, adjoining facility centre and service area analysis. ArcGIS Network Analyst helps users to dynamically model realistic network conditions which includes restrictions in limiting the speed, turning and transportation facilities in a day at different times. Users with Network Analyst can also find efficient traffic routes, determine the closest facility centre or vehicle, develop travel directions, and find a service area nearby.

The optimum route for collection of wastes was developed using Network Analyst based on two criteria: distance and time (Chimote and Bhambulkar 2012). Optimum routes were delineated using GIS and were less time-consuming and therefore, more cost-effective. Software-based analysis was simple to understand and very fast as compared to manual analyses.

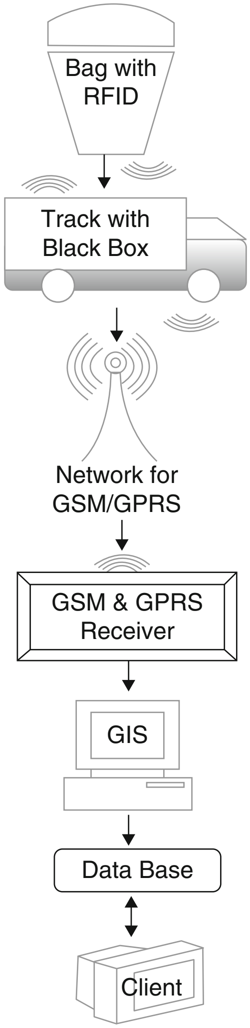
Using Radio Frequency Identification (RFID), GPS, GIS and GSM software, a model for solid waste monitoring and management system was developed which is shown schematically in Fig. 7.3. In this model, an RFID reader was loaded in the solid waste collection truck, by the help of which the location of bins, date and time of collection, weight and conditions was obtained (Purohit and Bothale 2011). This advanced technology provides information regarding real-time bin status, collection times, location of collection truck and other parameters that are useful for managing and monitoring collection of solid wastes from bins (Hannan et al. 2011). GIS along with mathematical programs and a computerized database management system can be used to explore different strategies for collection of solid wastes in different situations (Chang et al. 1997).

Analytical modelling and discrete-event simulation was applied to assess various scheduling and routing policies making use of real-time data. Dynamic scheduling and routing policies were found to have low operational expenses, shorter collection and transportation routes, less time consumption and reduced labour service time compared to the static scheduling policy with pre-determined routes and pick-up frequencies followed by operators (Johansson 2006).

3.4 Landfills Location Selection

No matter how municipal solid wastes are managed, final disposal of residual waste has to be done in landfills (Gbanie et al. 2013). Site selection for landfilling is a complex process where geological, hydrological, land use, sensitive sites, zoning regulations, air quality, environmental and geotechnical parameters as well as government regulations have to be considered. The landfill should have sufficient capacity to accommodate total waste to be deposited within 20–25 years. Various criteria have been proposed for landfill siting (Tchobanoglous et al. 1993; McDougall et al. 2003).

Fig. 7.3 Use of GPS and GIS in solid waste monitoring and management system



The most important points to be recognized in landfill siting as per MSWM rules, 2000 and its subsequent revision in 2016 are:

1. Site selection: The site selection shall be done with due consideration for environmental issues. The proposed landfill site should be away from water bodies, forest areas, national parks, wetlands and places of historical cultural or religious significance.
2. Distance from airports: To avoid birds from disturbing aircrafts during landing and take off, the landfill site should be located outside a 20 km radius from any airport/airbase.

3. Facilities at site: Proper fencing should be done at the entrance to monitor wastes/vehicles entering, to check the entry of cattle and to record proper documentation of entrance of vehicles and wastes.
4. Specifications for landfilling: The waste used for landfilling should be compressed in thin layers to maximise landfill capacity. Proper soil cover should be given. Drainage system should be provided to divert runoff water from the landfill site.
5. Pollution prevention: Storm water drains for diverting surface runoff from landfill site, non-permeable liner systems for base and walls of landfill and an appropriate leachate collection system are necessary to prevent contamination of surface and ground water resources. Collection of leachate and its treatment should be done as per given standards.
6. Water quality monitoring: Groundwater quality should be analyzed within 50 m surrounding the landfill site. Before construction of landfill site, groundwater quality should be monitored.
7. Ambient air quality monitoring: Gas collection system including its control should be done at landfill site to minimize the production of odour and to prevent migration of gases off-site. The concentration of methane gas generated at the landfill site should not exceed 25% of the lower explosive limit (LEL).
8. Plantation at landfill site: Plantation of some selected native species should be done on the completed site.
9. Closure of landfill site and post-closure care: The post-closure care of landfill site shall be conducted for 15 years and long-term monitoring should be done to assess if repairing of the final cover is required and the efficiency of the leachate collection system should be checked. After 15 years of post-closure care, the landfill area might be used for human settlement.
10. Special provisions for hilly areas: Definite methods for the solid waste disposal should be followed with consent of concerned SPCB/PCCs.

The above conditions will differ from place to place depending on the population distribution, meteorological, geological and hydrological conditions.

A multi-criteria decision analysis (MCDA) and overlay analysis using GIS was used for siting a suitable landfill (Sumathi et al. 2008). Various thematic layers were generated and integrated to obtain information such as soil type, drainage pattern, geology, topography, structure, and network and built-up area to determine best locations for landfill. A GPS was used to extract the exact coordinates of selected locations for landfill. Based on preliminary GIS screening and final fuzzy multi-criteria decision-making (FMCDM) assessment, the most appropriate site for the new landfill was selected (Chang et al. 2008).

Other benefits of conducting GIS in siting landfill include (Sumathi et al. 2008):

- Selection of zone segregation method in accordance to given screening criteria.
- Separation of zones and buffering.

- Conducting ‘what if’ data analysis and evaluating various potential scenarios associated with population growth and development of area and monitoring the significance of the various influencing aspects, etc.
- Managing and correlating large quantities of complex geographical data.
- Graphical representation of the results.

MCDM techniques were developed along with GIS and serve as major tools for decision makers. Recently, the combination of MCDM techniques with GIS was used to develop map overlays, advanced site suitability analysis and optimize solid waste management systems (Carver 1991; Eastman et al. 1997; Hazra et al. 2017 – Chap. 14 in this book).

3.5 Decision Support System

Decision Support Systems (DSS) are computer-based information systems to identify solutions to a problem. The application of Computer Based Information Systems (CBIS) makes the decision making process effective especially when large amounts of data have to be handled. The DSS models integrated with GIS can be used to optimize collection, transportation, processing and disposal methods for solid waste management.

DSS are a specific class of computerized information systems which provide a structured and logical basis for decision-making. All kinds of information can be compiled in these systems such as raw data, documents, personal knowledge and/or business models to resolve problems and propose suitable decisions. The fundamental structure of DSS consists of three components: database management, model base management, and user interface (Bani et al. 2009).

A web-based DSS for recycling and waste disposal was developed as shown in Fig. 7.4 (Bhargava and Tettelbach 1997).

In Finland, a MCDM model for the selection of proper treatment and disposal methods like incineration, landfilling, composting, refuse-derived fuel production and corresponding centralized/decentralized management model was developed (Hokkanen and Salminen 1997). An evaluation of knowledge-based decision support systems can be done for urban land use planning (Witlox 2005) while an Internet-based user interactive fuzzy multi-criteria decision support system was developed for regional and local integrated solid waste management (Zeng and Trauth 2005).

A multi-objective decision-making approach was used to design collection systems for municipal solid waste in India accounting for economic, environmental, technical and social aspects. The method depends on multi-objective lexicographic goal programming considering various alternatives. A period of five years was considered in the proposed model with Chennai city as a case study for SWM (Sudhir et al. 1996). GIS-based decision support systems for selection of sanitary landfill site were developed in another study (Natesan and Suresh 2002). Factors

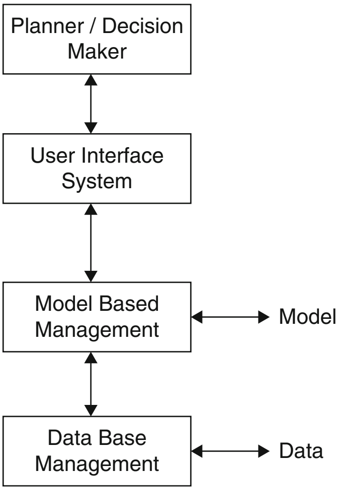


Fig. 7.4 Architecture of computer functionality in GIS

considered in this study were integrated land use, geology and geomorphology, drainage, slope of the area, soil, runoff, permeability characteristics, settlement and carrying capacity of the strata, ground water potential, susceptibility to erosion and absence of faults and joints. Grading for the above factors and their attributes was done using four Multi-Criteria Evaluation (MCE) models, viz., Analytical Hierarchy Process (AHP), Factor Importance Coefficient (FIC), Artificial Neural Networks (ANN) and Delphi. The best possible site was found by comparing all models. This method was used in the Chennai Metropolitan Development Area (CMDA), Chennai, India (Natesan and Suresh 2002).

Several decision support systems (DSS) have been developed and used in the field of municipal solid waste management. Improvement in DSS to make them user-friendly and adapt them for the management of solid waste within the Indian regulatory and social framework is necessary.

4 Miscellaneous Applications

GIS applications have been used as decision support systems recently by municipal authorities for effective execution of waste collection, transportation, reducing consumption of fuel, and developing work programme for workers and vehicles (Khajuria et al. 2011). GIS applications have been used to analyze maps and data that already exist (Sharholy et al. 2007). GIS applications were used to generate information regarding static and dynamic parameters in MSWM and optimize collection routing systems (Apaydin and Gonullu 2008).

Decision-support systems for solid waste management considering sustainability were adopted for diverting residential waste from the landfill site in Sahibzada Ajit Singh Nagar (John 2010). Backyard composting or vermi-composting, centralized composting of source-segregated organic waste, and centralized composting of mixed waste were considered as the three alternatives of the study. Based on six different identified criteria for sustainability of municipal solid waste processing methods, multi-criteria decision matrix involved the identification of different sustainability factors and parameters on the basis of socio-technical survey in this study area. Centralized composting of source-segregated organic waste was found to be the most feasible alternative (most preferred) under given conditions. Backyard composting or vermi-composting and centralized composting of mixed waste were second and third in order of preference based on sustainability criteria in decision making (John 2010).

5 Conclusions

Increase in the quantity of MSW generated along with poor collection efficiency leads to nuisance conditions and health hazards. Applications of RS and GIS in solid waste management have proved to be efficient and effective tools for improving waste collection in urban areas. GIS is capable of dealing with both spatial and non-spatial data and in combination with GPS can be used for designing successful solid waste collection systems. RS and GIS can provide preferable or optimal short routes which are cheap and efficient. GIS is a dynamic method for minimizing operational costs, and updating information regularly making the monitoring and management of urban space more transparent, timely and realistic.

References

Adeofun, C.O., Achi, H.A., Ufoegbune, G.C., Gbadebo, A.M. and Oyedepo, J.A., 2011. Application of Remote Sensing and Geographic Information System for Selecting Dumpsites and Transport Routes in Abeokuta., Nigeria. Proceedings of the Environmental Management Conference. http://www.unaab.edu.ng.

Agaji, I. and Wajiga, G., 2007. Computer Based Solid Waste Management for Nigerian Cities. An Agenda for Sustainable Development. *NASHER Journal*, **5(1)**, 75–78.

Apaydin, Omer and Gonullu, M. Talha, 2008. Emission Control with Route Optimization in Solid Waste Collection Process: A Case Study. *Sadhana*, **33(2)**, 71–82.

Babalola, Ayo and Busu, Ibrahim, 2011. Selection of Landfill Sites for Solid Waste Treatment in Damaturu Town Using GIS Techniques. *Journal of Environmental Protection*, **2**, 1–10. doi:10.4236/jep.2011.21001.

Balasooriya, B.M.R.S., Vithanage, M., Nawarathna, N.J., Ken Kawamoto, Zhang, M. and Herath, G.B.B., 2014. Solid Waste Disposal Site Selection for Kandy District, Sri Lanka: Integrating GIS and Risk Assessment. *International Journal of Scientific and Research Publications*, **4(10)**, 1–6.

Bani, M.S., Rashid, Z.A., Hamid, K.H.K., Harbawi, M.E., Alias, A.B. and Aris, M.J., 2009. The Development of Decision Support System for Waste Management: A Review. *World Academy of Science, Engineering and Technology*, **3**, 118–125.

Basavarajappa, H.T., Pushpavathi, K.N., Balasubramanian, A. and Manjunatha, M.C., 2012. Mapping and Integration of Geology and Geomorphological Landforms of Mysore District, Karnataka, India Using Remote Sensing and GIS Techniques. *Frontiers of Geosciences*, **1**, 64–75.

Bhambulkar, A.V., 2011. Municipal Solid Waste Collection Routes Optimized with ARC GIS Network Analyst. *International Journal of Advanced Engineering Sciences and Technologies*, **11**(1): 202–7.

Bhargava, H.K. and Tettelbach, C., 1997. A Web Based Decision Support System for Waste Disposal and Recycling. *Computers, Environment and Urban Systems*, **21(1)**, 47–65.

Brimicombe, A.J., 2003. A Variable Resolution Approach to Cluster Discovery in Spatial Data Mining. Chapter in *Computational Science and Its Applications* – ICCSA 2003, **2669**, 1–11. International Conference Montreal, Canada, May 18–21, 2003 Proceedings, Part III.

Carver, S.J., 1991. Integrating Multi-Criteria Evaluation with Geographical Information Systems. *International Journal of Geographical Information Systems*, **5(3)**, 321–339. doi:10.1080/02693799108927858.

Chalkias, C. and Lasaridi, K., 2009. A GIS Based Model for the Optimisation of Municipal Solid Waste Collection: The Case Study of Nikea, Athens, Greece. *WSEAS Transactions on Environment and Development*, **5(10):** 640–650. http://www.scopus.com/inward/record.url?eid=2-s2.0-71449113236&partnerID=40& md5=2b62a0a667c0b3241644d767d4b04cc2.

Chang, N.B., Lu, H.Y. and Wei, Y.L., 1997. GIS Technology for Vehicle Routing and Scheduling in Solid Waste Collection Systems. *Journal of Environmental Engineering*, **123(9):** 901–910. http://www.scopus.com/inward/record.url?eid=2-s2.0-0031475101&partnerID=40&md5=343b2541aad0bd0fcc7e4f9268107e95.

Chang, N.B, Parvathinathan, G. and Breeden, J.B., 2008. Combining GIS with Fuzzy Multicriteria Decision-Making for Landfill Siting in a Fast-Growing Urban Region. *Journal of Environmental Management*, **87**, 139–153. doi:10.1016/j.jenvman.2007.01.011.

Chimote, Kedar and Bhambulkar, Ashtashil, 2012. Municipal Solid Waste (MSW) Collection by Geographical Information System (GIS). National Conference on Innovative Paradigms in Engineering and Technology.

Choudhury, S. and Das, S., 2012. GIS and Remote Sensing for Landfill Site Selection-A Case Study on Dharmanagar Nagar Panchayet. *IOSR Journal of Environmental Science, Toxicology and Food Technology*, **1(2)**, 36–43. http://iosrjournals.org/iosr-jestft/papers/vol1-issue2/H0123643.pdf

Davami, A.H., Moharamnejad, N., Monavari, S.M. and Shariat, M., 2014. An Urban Solid Waste Landfill Site Evaluation Process Incorporating GIS in Local Scale Environment: A Case of Ahvaz City, Iran. *International Journal of Environmental Research*, **8(4)**, 1011–1018.

Deswal, Meena and Laura, J.S., 2014. Application of GIS in MSW Management in India. *International Journal of Engineering Research and Development*, **10(10)**, 24–32.

Eastman, J.R., Emani, S., Hulina, S., Jiang, H., Johnson, A. and Ramachandran, M., 1997. Applications of Geographic Information Systems (GIS) Technology in Environmental Risk Assessment and Management. UNEP, Division of Environmental Information and Assessment, Sioux Falls, SD.

Ebistu, Tirusew Ayisheshim and Minale, Amare Sewnet, 2013. Solid Waste Dumping Site Suitability Analysis Using Geographic Information System (GIS) and Remote Sensing for Bahir Dar Town, North Western Ethiopia. *African Journal of Environmental Science and Technology*, **7(11)**, 976–989. doi:10.5897/AJEST2013.1589.

Erham, E., Avraam, K., George, P. and Stevanus, A., 2008. A Multicriteria Facility Location Model for Municipal Solid Waste Management in North Greece. *European Journal of Operational Research*, **187(3)**, 1402–1421.

Gbanie, Solomon Peter, Paul Bobby Tengbe, Jinnah Samuel Momoh, James Medo and Victor Tamba Simbay Kabba, 2013. Modelling Landfill Location Using Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA): Case Study Bo, Southern Sierra

Leone. *Applied Geography*, **36** (January), Elsevier Ltd, 3–12. doi:10.1016/j.apgeog.2012.06.013.

Ghose, M.K., Dikshit, A.K. and Sharma, S.K., 2006. A GIS Based Transportation Model for Solid Waste Disposal – A Case Study on Asansol Municipality. *Waste Management*, **26**, 1287–1293. doi:10.1016/j.wasman.2005.09.022.

Goel, Sudha, 2008. Municipal Solid Waste Management (MSWM) in India: A Critical Review. *Journal of Environmental Science and Engineering*, **50(4)**, 319–328.

Hazra, T., Maitra, B.M. and Goel, S., 2017. Development and Application of a Multi-Criteria Decision Making (MCDM) Tool for solid waste management. Kolkata as a case study. Advances in Solid and Hazardous Waste Management. Capital Books, New Delhi and Springer, Switzerland.

Hannan, M.A., Arebey, M., Abdullah, H., Begum, R.A. and Basri, H., 2011. Solid Waste Monitoring and Management Using RFID, GIS and GSM. *Journal of Applied Sciences Research*, **7(12)**, 1961–1964. doi:10.1109/SCORED.2009.5443382.

Hokkanen, J. and Salminen, P., 1997. Choosing a Solid Waste Management System Using Multicriteria Decision Analysis. *European Journal of Operational Research*, **98**, 19–36. doi: Doi 10.1016/0377-2217(95)00325-8.

Hoornweg, D. and Bhada-Tata, P., 2012. What a Waste: A Global Review of Solid Waste Management.. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:WHAT+A+WASTE:+A+global+review+of+solie+waste+management#0.

Idowu, Adebayo P., Emmanuel, R. Adagunodo, Olapeju, A. Esimai and Tosin, C. Olapade, 2012. Development of A Web Based GIS Waste Disposal Management System for Nigeria. *International Journal of Information Engineering and Electronic Business*, **3**, 40–48. doi:10.5815/ijieeb.2012.03.06.

Javaheri, H., Nasrabadi, T., Jafarian, M.H., Rowshan, G.R. and Khoshnam, H., 2006. Site Selection of Municipal Solid Waste Landfills Using Analytical Hierarchy Process Method in a Geographical Information Technology Environment in Giroft. *Iran Journal of Environmental Health Science Engineering*, **3(3)**, 177–184.

Johansson, Ola M., 2006. The Effect of Dynamic Scheduling and Routing in a Solid Waste Management System. *Waste Management*, **26**, 875–885. doi:10.1016/j.wasman.2005.09.004.

John, S. 2010. Sustainability Based Decision-Support System for Solid Waste Management. *International Journal of Environment and Waste Management*, **6(1-2)**, 41–50.

Kanchanabhan, T.E., Abbas Mohaideen, J., Srinivasan, S. and Lenin Kalyana Sundaram, V., 2010. Optimum Municipal Solid Waste Collection Using Geographical Information System (GIS) and Vehicle Tracking for Pallavapuram Municipality. *Waste Management & Research*, **29(3)**, 323–339. doi:10.1177/0734242X10366272.

Karadimas, Nikolaos V. and Vassili G. Loumos, 2008. GIS-Based Modelling for the Estimation of Municipal Solid Waste Generation and Collection. *Waste Management & Research*, **26**, 337–346. doi:10.1177/0734242X07081484.

Katpatal, Y.B. and Rao, B.V.S.R., 2011. Decision Support System for Municipal Solid Waste Management of Nagpur Urban Area Using High-Resolution Satellite Data and Geographic Information System. *Journal of Urban Planning and Development*, **137**, 65–76. doi:10.1061/(ASCE)UP.1943-5444.0000043.

Khajuria, A., Matsui, T. and Machimura, T., 2011. GIS Application for Estimating the Current Status of Municipal Solid Waste Management System: Case Study of Chandigarh City, India. *Our Nature*, **9**, 26–33.

Khan, Debishree and Samadder, S.R., 2014. Application of GIS in Landfill Siting for Municipal Solid Waste. *International Journal Environmental Research and Development*, **4(1)**, 37–40.

Kumar, Sunil and Mohammad Izhar Hassan, 2013. Selection of a Landfill Site for Solid Waste Management: An Application of AHP and Spatial Analyst Tool. *Journal of the Indian Society of Remote Sensing*, **41(1)**, 45–56. doi:10.1007/s12524-011-0161-8.

Liebman, J.C., Male, J.W. and Wathne, M., 1975. Minimum Cost in Residential Refuse Vehicle Routes. *Journal of Environmental Engineering Division*, **101**, 399–412.

Malakahmad, Amirhossein, Putri Bakri, Muniah Radin Mokhtar and Noordiana Khalil, 2014. Solid Waste Collection Routes Optimization via GIS Techniques. *Procedia Engineering*, **77** Elsevier B.V., 20–27. doi:10.1016/j.proeng.2014.07.023.

Mănoiu, Valentina, Iulia Fontanine, Romulus Costache, Remus Pravalie and Iulian Mitof, 2013. Using GIS techniques for assessing waste landfill placement suitability. Case study: Prahova County, Romania, *Geographia Technica*, **8(2)**, 47–56.

McDougall, F.R., White, P.R., Franke, M. and Hindle, P., 2003. Integrated Solid Waste Management: A Life Cycle Inventory. doi:10.1016/S0956-053X(02)00032-6.

Muriithi, David and Mutua, Felix, 2012. Eco-Taka: An Efficient GIS Based Solid Waste Management Solution. *International Journal of Science and Research*, **3(9)**, 1016–1022.

Natesan, Usha and Suresh, E.S.M., 2002 Site Suitability Evaluation for Locating Sanitary Landfills Using GIS. *Journal of the Indian Society of Remote Sensing*, **30(4)**, 261–264. doi:10.1007/BF03000369.

Nishant, T., Prakash, M.N. and Vijith, H., 2010. Suitable Site Determination for Urban Solid Waste Disposal Using GIS and Remote Sensing Techniques in Kottayam Municipality, India. *International Journal of Geomatics and Geosciences*, **1(2)**, 197–210.

Nithya, R., Velumani, A. and Senthil Kumar, S.R.R., 2012. Optimal Location and Proximity Distance of Municipal Solid Waste Collection Bin Using GIS: A Case Study of Coimbatore City. *WSEAS Transactions on Environment and Development*. **8(4)**, 107–119. doi:10.11648/j.ajaf.20140206.20.

Ohri, A. and Singh, P.K., 2010. Development of Decision Support System for Municipal Solid Waste Management in India: A Review. *International Journal of Environmental Sciences*, **1(4)**, 440–453.

Oyinloye, Michael Ajide, 2013. Using GIS and Remote Sensing in Urban Waste Disposal and Management. *European International Journal of Science and Technology*, **2(7)**, 106–118. www.eijst.org.uk.

Padmaja, V., Asadf, S.S. and Anji, M.R., 2006. Solid Waste Disposal Site Selection Using Analytical Hierarchy Process and GIS. *Pollution Research*, **25(1)**, 73–76.

Purohit, Suchit S. and Bothale, Vinod M., 2011. RFID Based Solid Waste Collection Process. *IIM Ahmedabad Newsletter*. doi:10.1109/RAICS.2011.6069354.

Reddy, M.A., 2005. Hierarchy Process (AHP) – GIS Model for Landfill Siting: A Case Study of Hyderabad City, India. International Conference on Environmental Management (ICEM).

Reddy, M.A. and Padmaja, V., 2007. Development of GIS Based Decision Support Tool for Optimal Route Analysis for Transportation of Solid Waste. Proceeding of 22nd International Conference on Solid Waste Technology and Management Philadelphia PA USA

Saxena, S., Srivastava, R.K. and Samaddar, A.B., 2010. Towards Sustainable Municipal Solid Waste Management in Allahabad City. *Management of Environmental Quality: An International Journal*, **21(3)**, 308–323. doi:10.1108/14777831011036876.

Saxena, S. and Srivastava, R.K., 2011. GIS for Site Selection for MSW Landfills. *Proceedings of Indian Geotechnical Conference*, 793–796.

Şener, Şehnaz, Sener, Erhan and Karagüzel, Remzi, 2011. Solid Waste Disposal Site Selection with GIS and AHP Methodology: A Case Study in Senirkent-Uluborlu (Isparta) Basin, Turkey. *Environmental Monitoring and Assessment*, **173**, 533–554. doi:10.1007/s10661-010-1403-x.

Senthil, J., Vadivel, S. and Murugesan, J., 2012. Optimum Location of Dust Bins Using Geo-Spatial Technology: A Case Study of Kumbakonam Town, Tamil Nadu, India. *Advances in Applied Science Research*, **3(5)**, 2997–3003.

Sharholy, Mufeed, Kafeel Ahmad, Vaishya, R.C. and Gupta, R.D., 2007. Municipal Solid Waste Characteristics and Management in Allahabad, India. *Waste Management*, **27**, 490–496. doi:10.1016/j.wasman.2006.03.001.

Shoba, B. and Rasappan, K., 2013. Application of GIS in Solid Waste Management for Coimbatore City. *International Journal of Scientific and Research Publications*, **3(10)**, 1–4.

Shukla, Gaurav, Shashi, M. and Jain, Kamal, 2012. Decision Support System for Selecting Suitable Site for Disposing Solid Waste of Township. *International Journal of Remote Sensing and GIS*, **1(1)**, 2–11.

Siddam, Samidha, Khadikar, Isha and Chitade, Anil, 2012. Route Optimisation for Solid Waste Management Using Geo-Informatics. *IOSR Journal of Mechanical and Civil Engineering*, **2(1)**, 78–83.

Son, Le Hoang, 2014. Optimizing Municipal Solid Waste Collection Using Chaotic Particle Swarm Optimization in GIS Based Environments: A Case Study at Danang City, Vietnam. *Expert Systems with Applications*, **41**, Elsevier Ltd, 8062–8074. doi:10.1016/j.eswa.2014.07.020.

Sudhir, V., Muraleedharan, V.R. and Srinivasan, G., 1996. Integrated Solid Waste Management in Urban India: A Critical Operational Research Framework. *Journal of Socio Economic Planning Sciences*, 30(3), 163–181. http://www.sciencedirect.com/science/article/pii/0038012196000122.

Sule, J.O., Aliyu, Y.A. and Umar, M.S., 2014. Application of GIS in Solid Waste Management in Chanchaga Local Government Area of Niger State, Nigeria. *IOSR Journal of Environmental Science, Toxicology and Food Technology*, **8(9)**, 17–21.

Sumathi, V.R., Natesan, Usha and Sarkar, Chinmoy, 2008. GIS-Based Approach for Optimized Siting of Municipal Solid Waste Landfill. *Waste Management*, **28**, 2146–2160. doi:10.1016/j.wasman.2007.09.032.

Tchobanoglous, G., Theisen, H. and Vigil, S.A., 1993. Integrated Solid Waste Management: Engineering Principles and Management Issues. McGraw Hill International, Singapore. Civil Engineering Series.

Twumasi, Yaw A, and Edmund C Merem. 2007. "Using Remote Sensing and GIS in the Analysis of Ecosystem Decline along the River Niger Basin: The Case of Mali and Niger." Int. J. Environ. Res. Public Health **4(2)**: 173–84.

Velumani, A., 2014. Development Research. *International Journal of Development Research*, **4(1)**, 100–104.

Vijay, Ritesh, Gautam, Ajay, Kalamdhad, Ajay, Gupta, Apurba and Devotta, Sukumar, 2008. GIS-Based Locational Analysis of Collection Bins in Municipal Solid Waste Management Systems. *Journal of Environmental Engineering and Science*, **7**, 39–43. doi:10.1139/s07-033.

Witlox, Frank, 2005. Expert Systems in Land-Use Planning: An Overview. *Expert Systems with Applications*, **29**, 437–445. doi:10.1016/j.eswa.2005.04.041.

Zeng, Y. and Trauth, K., 2005. Internet-Based Fuzzy Multicriteria Decision Support System for Planning Integrated Solid Waste Management. *Journal of Environmental Informatics*, **6(1)**, 1–15. doi:10.3808/jei.200500050.

Chapter 8
Environmental Impacts of Pond Ash Dumping at Kolaghat Thermal Power Plant (KTTP) – Physico-chemical Characterization of Pond Ash

Prasenjit Ghosh and Sudha Goel

1 Introduction

One of the major sources of pollution in the modern world of industrialization and urbanization is the generation of large quantities of Coal Combustion Residue (CCR) from the combustion of coal in thermal power plants. CCRs include fly ash, bottom ash and pond ash. When pulverized coal is burnt to generate heat, the residue collected from different rows of electrostatic precipitators in dry form contains 80% fly ash. It is an important resource for production of Portland Pozzolana Cement, a replacement of ordinary Portland cement. 20% of residue of burnt coal, collected in the water-impounded hopper below the boilers is called bottom ash. It is generally used for fills, embankments and road construction. Pond ash is a mixture of bottom ash and fly ash as available in ash ponds. It is a resource material for manufacturing clay ash bricks, filling material for area development, construction of embankments etc.

Thermal Power Plants (TPPs) which generate more than 60% of the electricity in India are responsible for generation of huge quantity of CCRs. During the years 2010–2012, about 408 MT/year of coal was used and more than 130 MT/year of fly ash was generated by 88 TPPs all over India.

Generation of CCRs has become a serious problem due to the enormous space requirement for their disposal. Wet disposal of CCRs has serious environmental concerns due to leaching of toxic, heavy metals into the aqueous phase. When fly

---

P. Ghosh (✉)
Centre for Environmental Science and Engineering, Indian Institute of Technology Bombay,
Powai, Mumbai 400076, India
e-mail: ami.prasenjit@gmail.com

S. Goel
Civil Engineering Department, Indian Institute of Technology Kharagpur,
Kharagpur 721302, WB, India

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_8

ash remains in dry state, it creates dust problems, increasing the level of suspended particulate matters in the air. As the particle size of the dust varies from submicron to micron range, it can cause serious respiratory problems.

In the present study, different physical and chemical properties of pond ash (collected from three different ash ponds around Kolaghat Thermal Power Plant) and soil samples (collected from neighbouring ground of Civil Engineering Department at IIT Kharagpur) were determined.

2 Materials and Methods

The area around Kolaghat Thermal Power Plant (KTPP) was the study area for this research. Sample collection, and different experimental methods for physicochemical characterization of the samples are detailed in this chapter.

2.1 Description of Study Area

KTPP is located (22°10′N and 88°00′E) on the West bank of Rupnarayan at Mecheda in the district of East Midnapur, West Bengal. It has a total installed capacity of 1260 MW with six units, generating about 7500–8000 MT of fly ash every day by consuming a total of 18,000 tonnes of coal/day (mainly bituminous). Presently, the plant has only 325 acres of land for fly ash dumping purpose (Dasgupta and Paul 2011). The location of the plant is shown in Fig. 8.1 and different views of the plant are shown in Fig. 8.2.

2.2 Sample Collection

Details of different sample collections are provided in this section.

2.2.1 Pond Ash Samples

Three pond ash samples were collected from three different ash ponds situated around Kolaghat Thermal Power Plant (KTPP) in West Bengal on 17th February, 2013. Figure 8.2 includes a satellite image from Google Earth of KTPP and a ground view of the plant. The first row of photos in Fig. 8.3 shows satellite images of the three pond ash sample collection sites, and the second row includes photos of

Fig. 8.1 Location of KTPP in the Map of West Bengal

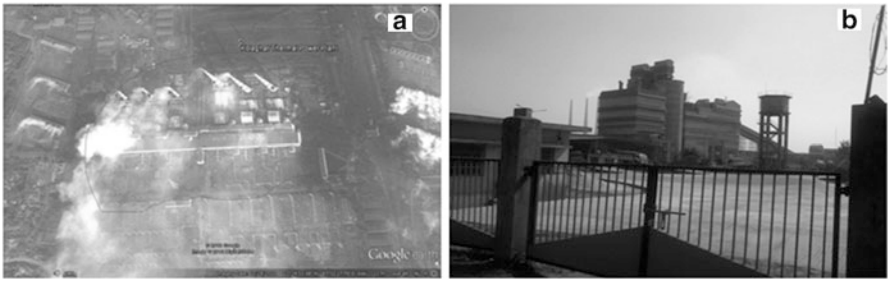


Fig. 8.2 Satellite image and outside view of KTPP

the pond ash collection sites taken personally. Samples were collected in plastic buckets and were immediately sealed with plastic cover to prevent exposure to sunlight. Pond ash samples were named as pond ash samples 1, 2 and 3 according to the sequence of their collection and the same is followed henceforth.

Fig. 8.3 Pictorial views of Pond ash collection sites

2.2.2 Soil Samples

One background soil sample was collected from the ground around Civil Engineering Department, IIT Kharagpur on 27th February, 2014. It was collected in a plastic bucket and was immediately sealed with plastic cover to prevent exposure to sunlight.

2.3 Physical and Chemical Characterization of Solid Samples

Detailed physical and chemical characterization of the samples was necessary prior to conducting any other test. Materials and methods used for doing so are described in this section.

2.3.1 Solids Analyses

Total, volatile and fixed solid contents of the pond ash and soil samples were measured following Method 2540G in Standard Methods for the Examination of

Water and Wastewater (APHA, AWWA and WEF 2005). Different formulae used for calculation of different solid contents are given below:

$$\%\text{Total solids} = \frac{(A - B)}{(C - B)} \times 100 \tag{8.1}$$

$$\%\text{Volatile solids} = \frac{(A - D)}{(A - B)} \times 100 \tag{8.2}$$

$$\%\text{Fixed solids} = \frac{(D - B)}{(A - B)} \times 100 \tag{8.3}$$

where A = Weight of (dried residue + crucible), B = Weight of dried crucible, C = Weight of (wet sample + crucible) and D = Weight of (residue + crucible) after ignition.

2.3.2 Specific Gravity and Bulk Density

Specific gravity of the pond ash samples was determined by density bottle method following IS: 2720-Part III (Sect. 2). Following formulae were used for calculation of specific gravity.

$$\text{Specific gravity of pond ash at T °C}, G_T = \frac{M_2 - M_1}{[(M_2 - M_1) - (M_3 - M_4)]} \tag{8.4}$$

The value of specific gravity depends on the temperature hence its value is reported as standard temperature of 27 °C.

$$\text{Specific gravity of pond ash at 27 °C}, G_{27} = G_T \times \left(\frac{\rho_{WT}}{\rho_{W27}}\right) \tag{8.5}$$

where, M_1 = Mass of empty density bottle (g), M_2 = Mass of density bottle + soil grains (g), M_3 = Mass of empty density bottle + soil grains + water (g) and M_4 = Mass of empty density bottle + water (g).

Density of water at T °C = ρ_{WT} g/cm^3
Density of water at 27 °C, $\rho_{\mathrm{W27}} = 0.996512$ g/cm^3

For measuring bulk densities of the pond ash samples, at first some amount of pond ash was taken into a cylindrical steel mould of known dimensions. Then it was compacted in three layers and filled up to the top. With the help of a knife, the sample was trimmed to a more regular shape. Then the sample was taken out by loosening the screws of the mould. The sample was then weighed on a balance (M). The formula used for calculating bulk density of pond ash samples is given below:

$$\text{Bulk density, } \rho_b = \left(\frac{M}{V}\right)\text{g/cm}^3 \tag{8.6}$$

where, V = Volume of the cylindrical mould cm^3.

2.3.3 Specific Surface Area

Specific surface areas of all the three pond ash samples were determined by Air Permeability Method (Blaine method). It is a measure of the fineness of a sample. It is expressed as the total surface area in square metres of all the particles of a sample in 1 kilogram of the same. Cement was used as the reference material for calibration of the Air Permeability Apparatus. The higher the specific surface area, the finer is the sample. IS: 4031 (Part 3) was followed to perform the experiment. The following formula was used for calculating fineness.

$$\text{Fineness} = K\sqrt{t}\left(\text{cm}^2/\text{g}\right) \tag{8.7}$$

where, K = Apparatus constant (Value of K was 426 for the instrument used for the experiment) and t = Average time taken (sec) by mercury to fall to a certain height within a pipe in the instrument.

2.3.4 Hydraulic Conductivity (K) and Particle Size Distribution

Hydraulic conductivity was determined by Falling Head Permeability Method for all the pond ash samples along with the background soil sample. As the samples were fine grained and non-adhesive in nature, so neither constant head permeability method (appropriate for coarse grained sample) nor consolidation test (appropriate for clayey sample) was appropriate.

Particle size distribution curves of all the three pond ash samples were obtained after sieve and hydrometer analyses on the same. Sieves of sizes 4.75 mm, 2 mm, 1 mm, 425 μ, 300 μ, 150 μ and 75 μ were used for sieve analyses. Fraction passing through 75 μ sieve was used for hydrometer analyses. Different values of % finer and grain size of all the samples were combined to plot particle size distribution graphs.

Hydraulic conductivity of sample at room temperature (T °C),

$$K_T = \left(\frac{aL}{At}\right)\ln\left(\frac{h_1}{h_2}\right) \tag{8.8}$$

$$\Rightarrow \qquad K_T = \left(\frac{d}{D}\right)^2 \ln\left(\frac{h_1}{h_2}\right) \times \left(\frac{L}{t}\right) \text{ and } K_{20} = K_T \times \left(\frac{\mu_T}{\mu_{20}}\right) \qquad (8.9)$$

where, A = Cross sectional area of mould (cm^2), a = Cross sectional area of stand pipe (cm^2), L = Length of sample (cm), t = Time required for water to come down from zero level to the required level in the standpipe (sec), h_1 = Height of zero level of stand pipe from the centre of the effluent nozzle of the apparatus (cm), h_2 = Height of required level in stand pipe from the centre of the effluent nozzle of the apparatus (cm), d = Diameter of the stand pipe (1.03 cm), D = Diameter of the mould (7.2 cm), K_T = Hydraulic conductivity of the sample at room temperature (cm/sec), K_{20} = Hydraulic conductivity of the sample at 20 °C (cm/sec), μ_T = Viscosity of water at T °C (dyne-sec/cm^2).

2.3.5 HRTEM Observations of Pond Ash Particles

Shape and size of the particles present in the pond ash samples were studied using JEM-2100 HRTEM at operating voltage of 200 KV. HRTEM samples were prepared as follows: few mg of samples were dispersed in acetone by ultrasonication and appropriately deposited on carbon-covered copper grids and then dried. The copper grids containing ash particles were fixed up on an HRTEM stub and were observed by randomly selecting larger fields of view. Size and morphology of the particles were examined.

2.3.6 SEM-EDS Analyses of Pond Ash Samples

SEM and EDS analyses were done on all the pond ash samples. Scanning electron microscope is capable of providing imaging information and surface texture of individual particles of a sample, while Energy-dispersive X-ray Spectroscopy (EDS) is capable of providing elemental composition of the surfaces of sample particles. JEOL JSM5800 scanning electron microscope with Oxford EDS Detector was used for the analyses.

Regarding sample preparation for SEM-EDS test, a very small amount of sample was put on a double-sided adhesive and conductive carbon tape with the help of a clean wooden pick. Subsequently, gentle blowing was applied to remove loosely attached particles away. Then the carbon tape with remaining particles was taken inside the instrument for analyses.

2.3.7 Oxide Composition

Different oxide compositions of the pond ash samples were determined during their EDS analyses.

2.3.8 Optimum Moisture Content (OMC) and Maximum DryDensity (MDD)

The optimum moisture content and maximum dry density of all the samples (pond ash and background soil) were determined by performing Standard Proctor Compaction Test on the same. "ASTM D 698-Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort" was followed to perform the tests. All the samples tested were the fraction passing through IS 4.75 mm sieve. They were compacted in three layers each with 25 numbers of blows with a 2.6 kg hammer (attached to an Automatic Compactor). Graphs were plotted of dry density versus moisture content to obtain OMC and MDD.

2.3.9 Surface Reactivity of Pond Ash

The surfaces of pond ash particles are considered to be more chemically reactive than the interior (Neupane and Donahoe 2013). The surface reactivity of pond ash samples was determined by measuring the pH values of water-pond ash mixtures immediately after addition of water and after some equilibration time followed by stirring and settling. Reagent grade water was used for performing all the tests. The effects of stirring and settling of the pond ash-water slurries on pH of the sample supernatant over a time period of 15 days were also studied.

3 Results and Discussions

3.1 Physical and Chemical Characterization of PondAsh and Soil

Results of physical and chemical characterization of pond ash, and background soil samples are described here.

3.1.1 Solids Content of Pond Ash and Soil Samples

Solids content of the different pond ash samples and one background soil sample are summarized in Table 8.1. Water content was almost negligible ($\geq 1\%$) in all the pond ash samples. However, it was significant in the soil sample ($>16\%$). Volatile solids were less than 10% of the total solids in all the four samples. Among the pond ash samples, sample 3 had the highest content of volatile solids (8.95%) while the background soil sample had moderate volatile solid content (7.4%).

Table 8.1 Solids analyses for pond ash (PA) and soil samples

Parameters	PA-I	PA-II	PA-III	Soil
A (g)	27.566	37.681	28.521	27.707
B (g)	26.57	36.69	27.53	26.874
C (g)	27.567	37.686	28.531	27.874
D (g)	27.509	37.601	28.432	27.645
TS in %	99.91	99.51	99	83.32
TS in g/g	0.999	0.995	0.99	0.833
VS in %	5.675	7.999	8.949	7.381
VS in g/g	0.056	0.08	0.089	0.073
FS in %	94.325	92.001	91.051	92.619
FS in g/g	0.943	0.92	0.91	0.926

3.1.2 Specific Gravity and Bulk Density

It can be seen from the results shown in Tables 8.2 and 8.3 that pond ash sample 3 had highest specific gravity while ash sample 2 had highest bulk density.

3.1.3 Specific Surface Area

Specific surface area of a sample represents fineness of the same. Table 8.4 shows fineness values of the pond ash samples. Pond ash sample 2 had the maximum specific surface area comparable to that of Portland cement (300–500 m^2/kg) and pond ash sample 3 had the lowest specific surface area. Sample 1 had moderately low permeability. If specific surface area increases, a sample may prove to be a threat to environment, as more elements will get adsorbed on its surfaces. During leaching, these adsorbed elements will be released into the percolating medium increasing the extent of contamination of the leachate. So, pond ash sample 2 may prove to be a greater threat to environment.

3.1.4 Hydraulic Conductivity and Particle Size Distribution

Hydraulic conductivity values of different pond ash samples along with one background soil sample are listed in Table 8.5.

From the results of falling head permeability tests shown in Table 8.5, it can be concluded that pond ash sample 3 was highly permeable whereas, pond ash sample 1 was moderately permeable. On the other hand, pond ash sample 2 and the background soil sample were poorly permeable. So, if we consider only permeability factor, then pond ash samples 1 and 3 are less potent for leaching of different elements present in them. However in case of pond ash sample 2, the contact time of the percolating medium with the sample will be higher and that may result in greater leaching of the elements present in the sample.

Table 8.2 Specific gravity of pond ash samples

Parameters	Sample 1	Sample 2	Sample 3
M_1 (g)	31.35	32.56	32.09
M_2 (g)	44.87	44.61	45.16
M_3 (g)	140.56	140.47	141.86
M_4 (g)	133.58	134.18	134.84
T (°C)	30	30	30
ρ_{WT}	0.995646	0.995646	0.995646
G_T	2.067	2.09	2.162
G_{27}	2.065	2.088	2.158

Table 8.3 Bulk density of pond ash samples

Description	Sample 1	Sample 2	Sample 3
Weight of moulded sample (g)	99.54	100.99	101.52
Volume of mould (cm^3)	86.196	86.196	86.196
Bulk density, ρ_b (g/cm^3)	1.155	1.172	1.177

Table 8.4 Fineness of pond ash samples

Samples	t_1 (sec)	t_2 (sec)	t_3 (sec)	t (arg) sec.	K	Fineness (m^2/kg)
Pond ash I	3	3	3	3		73.78
Pond ash II	35	36	36	35.67	426	254.41
Pond ash III	1.5	2	1.8	1.77		56.62

Table 8.5 Hydraulic conductivity of pond ash and soil samples

Parameters	Pond ash sample I	Pond ash sample II	Pond ash sample III	Soil sample
h_1 (cm)	78.6	78.6	78.6	78.6
h_2 (cm)	58.6	73.6	48.6	48.6
t (avg) sec.	65.82	411.33	33.59	326.67
L (cm)	13.2	12.8	12.2	12.2
T (°C)	28.5	29	28	20
K_T (cm/sec)	0.001205	0.00004186	0.003573	0.0004186
K_{20} (cm/sec)	0.000992	0.00003407	0.002972	0.0004186
Nature of sample	Moderately permeable	Poorly permeable	Highly permeable	Poorly permeable

From particle size distribution graph shown in Fig. 8.4, it was observed that D_{50} of pond ash samples 2 and 1 are similar (both approximately 18 micron) and for pond ash sample 3 it is 75 micron. This gives the median diameter of the particles present in those samples. Table 8.6 summarizes the observations made from the experimental data and graph (Fig. 8.4) of Particle Size Distribution experiment.

From Table 8.6, it can be concluded that pond ash sample 2 had highest content of silt/clay size particles which may be the reason of its poor permeability.

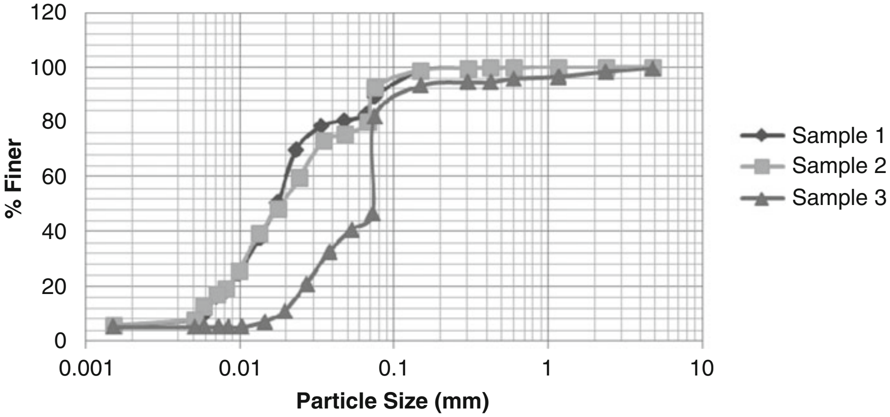


Fig. 8.4 Particle size distribution graphs of three different pond ash samples

Table 8.6 Summary of results of particle size distribution

Parameters	Sample 1	Sample 2	Sample 3
Gravel % (>4.75 mm)	0.03	0.024	0.436
Sand % (0.075–4.75 mm)	10.698	7.344	17.76
Silt/Clay % (<0.075 mm)	89.272	92.632	81.804
D_{10} (mm)	0.005	0.006	0.018
D_{30} (mm)	0.012	0.012	0.034
D_{60} (mm)	0.02	0.025	0.07
Uniformity coefficient (C_u)	4	4.17	3.89
Coefficient of curvature (C_c)	1.44	0.96	0.917

3.1.5 HRTEM Images of Pond Ash Particles

Figure 8.5 depicts shapes and sizes of three pond ash samples observed under high resolution transmission electron microscope. Pond ash samples 1 and 3 were mostly irregular shaped particles but pond ash sample 2 was mostly spherical particles. Selected area (electron) diffraction images are also shown in Fig. 8.5. Particle sizes of all the pond ash samples were less than 1 μm.

3.1.6 SEM-EDX of Pond Ash Samples

Observing the SEM images of the pond ash samples as shown in Fig. 8.6, it can be concluded that the particles were mainly made up of irregular spherical, semi-spherical and sometimes irregular grains. First row of figures shows SEM images of particles in pond ash sample 1. The second and third rows represent SEM images of 2nd and 3rd pond ash samples respectively. On close observation of pond ash particles, distribution of finer particles can be seen over surfaces of larger particles.

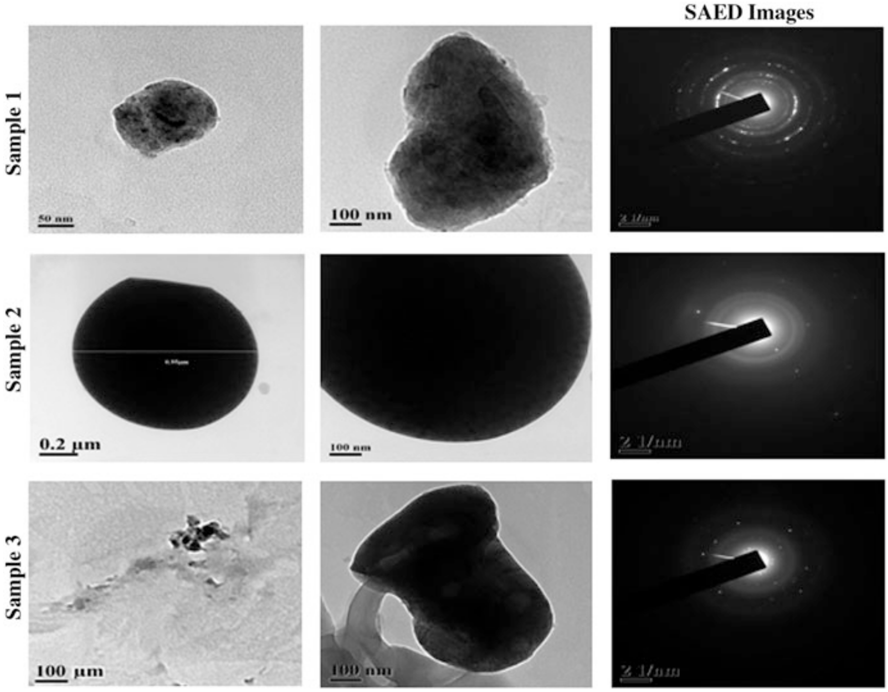


Fig. 8.5 HRTEM images of three pond ash samples

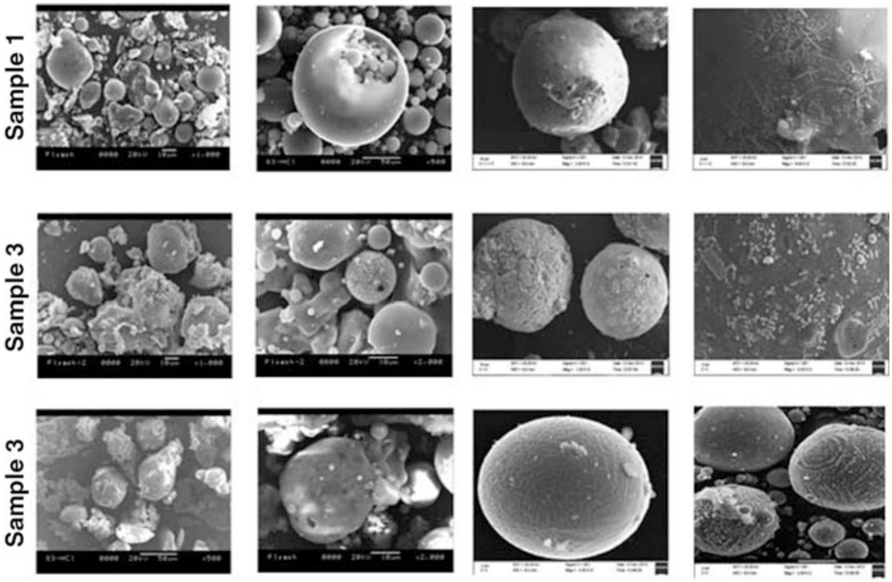


Fig. 8.6 SEM images of pond ash samples

They may be either different minerals or elements bound on the pond ash particle surfaces. The surface materials of the pond ash samples may leach in contact with percolating medium. The nonsphericity of pond ash particles is correlated with coal combustion efficiency and probably with the black carbon to total particle mass ratio. Martins et al. (1998) argued that higher coal combustion efficiencies produce high black carbon contents and the particles produced are mostly nonspherical. However, Tang et al. (2013) concluded that lower or incomplete coal combustion produces ash particles of irregular shape. So, there is a controversy regarding the relation between combustion efficiency and ash particle sphericity.

EDS spectra were used to determine the elemental composition of the pond ash samples (Ghosh 2014). Al, Si and O were present in significant quantities in all three samples that were tested. These three elements are known to be the most abundant elements in the earth's crust and their dominant presence in pond ash is natural since these are non-combustible materials. Some amount of C was present in pond ash sample 1 and very high C content was observed in sample 3; in case of pond ash sample 2 it is absent and is indicative of combustion efficiency. The high C content of sample 3 shows incomplete combustion of coal and is probably related to the higher particle size and greater sphericity of the particles.

Other elements such as K, Ca, Mg, Ti, Fe, Cu, Zn, As, Se and Cd are present in very less amounts (absent in some cases). So the ash samples may prove to be toxic due to presence of Cu, Zn, As and Cd (although in trace amounts).

3.1.7 Oxide Composition

Since fly ash is the dominant component in pond ash (more than 80%), some conclusions can be made about the type of fly ash present in the pond ash samples. There are two types of fly ash produced from coal combustion, types F and C. Type F fly ash is produced when anthracite or bituminous or sub-bituminous coal is burnt and is low in lime (<7%) and contains more silica, alumina and iron oxide. Type C fly ash comes from lignite coal combustion and contains more lime (Iyer 2002).

It is observed from Table 8.7 that lime is present in very less amount (<7%) in pond ash sample 2. In other samples it is absent. Oxide of Si is dominant in all three pond ash samples. Oxides of Al and Fe are present in two out of the three pond ash

Table 8.7 Different oxide components of three pond ash samples

	% in different pond ash samples		
Different oxides	Sample 1	Sample 2	Sample 3
Al_2O_3	37.27	19.67	0
SiO_2	54.77	59.09	66.17
K_2O	7.95	2.39	6.79
CaO	0	2.42	0
TiO_2	0	4.19	0
FeO	0	12.25	24.66
AS_2O_3	0	0	2.38

samples tested. So the fly ash present in the pond ash samples can be classified as Class F.

CaO and MgO components in the pond ash samples are negligible (CaO was present only in sample 2 and MgO was absent in all the samples). So it can be concluded that the pond ash samples were acidic in nature (Izquierdo and Querol 2012).

Another conclusion can be made regarding the type of coal burnt in the Kolaghat Thermal Power Plant, which is one of bituminous or sub-bituminous or anthracite (Iyer 2002). It is known from the source at Kolaghat Thermal Power Plant that bituminous and sub-bituminous coals are burned there. So, the experimental results match with the information.

3.1.8 Optimum Moisture Content (OMC) and Maximum DryDensity (MDD)

Comparing different values of OMC, MDD and permeability obtained for the three pond ash samples, a general tendency can be observed. As OMC increases, MDD value decreases but value of K increases. So, there is a positive correlation between OMC and K and negative correlation between OMC and MDD of the ash samples. This implies that pond ash sample 2 can be more densely compacted in the field compared to other pond ash samples. It is better material to be used for land filling compared to the other two pond ash samples (Fig. 8.7, Table 8.8).

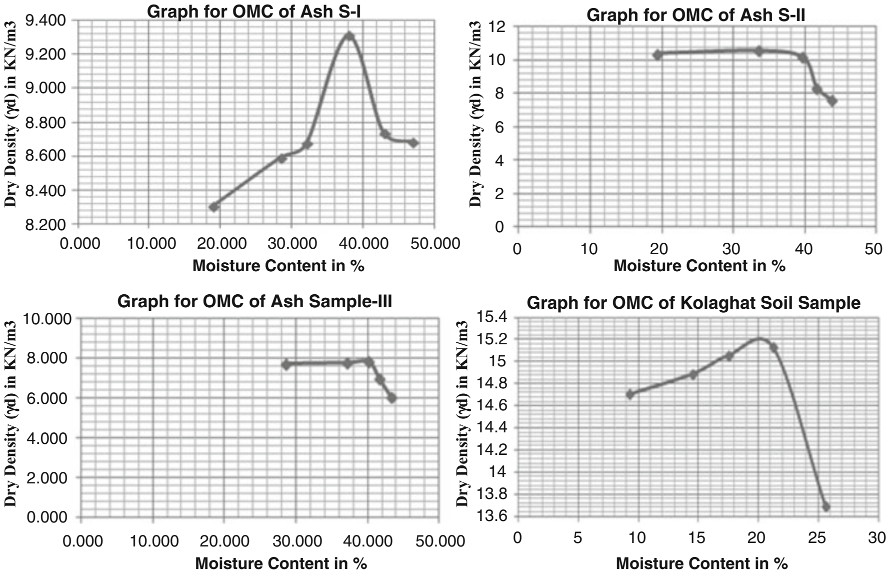


Fig. 8.7 Variation of dry density with moisture content of different samples

Table 8.8 OMC, MDD and permeability of different solid samples

Samples indentification	OMC (%)	MDD (kN/m^3)	Permeability, K (cm/sec)
Pond ash I	38	9.32	0.000992
Pond ash II	33	10.6	0.0000341
Pond ash III	40	7.8	0.002972
Soil	20.3	16.21	0.0004186

3.1.9 Surface Reactivity of Pond Ash

Surface reactivity experiments were conducted by mixing different concentrations of pond ash samples with reagent grade water for varying periods of time. Initial pH, pH after stirring and settling for 1 h and pH after 24 h of settling of pond ash slurries at different concentrations are shown in Fig. 8.8. It can be concluded from the graphs that pH of the samples were mostly mass independent and ranged from 6 to 7.5. The pH of the solution after 24 h of settling fell to values ranging from 3.5 to 5.

The long-term effects of stirring and settling of the pond ash-water slurries on pH of the sample supernatant over a period of 15 days are shown in Fig. 8.9. In general, the greatest drop in pH in all samples and at all concentrations occurred in the first 24 h, with a slow decline over the remaining period of time. The pH dropped to an average value of 3.86 and the lowest recorded pH was 3.5. These results suggest that leachate or surface runoff from wet dumps of pond ash can have very low pH resulting in further adverse impacts on soil and aqueous environments and in mobilization of toxic heavy metals in the environment.

4 Conclusions

The following conclusions can be made from the above studies:

(i) Silt/clay particles were mostly found in the pond ash samples. D_{50} values for samples 1 and 2 were 18 microns, while sample 3 had a value of 75 microns. All particles were found to be >1 micron in size, i.e., the fraction of sub-micron sized particles was not measurable. The last sample also had very high C content indicating incomplete combustion of coal. Al, Si and O were dominant elements in all pond ash samples.

(ii) Pond ash sample 2 can be used in cement production. At the same time due to higher specific surface area, adsorption of heavy metals may take place in wet landfill environment. So there remain chances of contamination of soil media underlying the pond ash layers. Pond ash sample 2 may prove to be a threat to the environment (soil and ground water) during rainfall as leaching of heavy metals may occur at that time at much higher rate due to higher contact time with water.

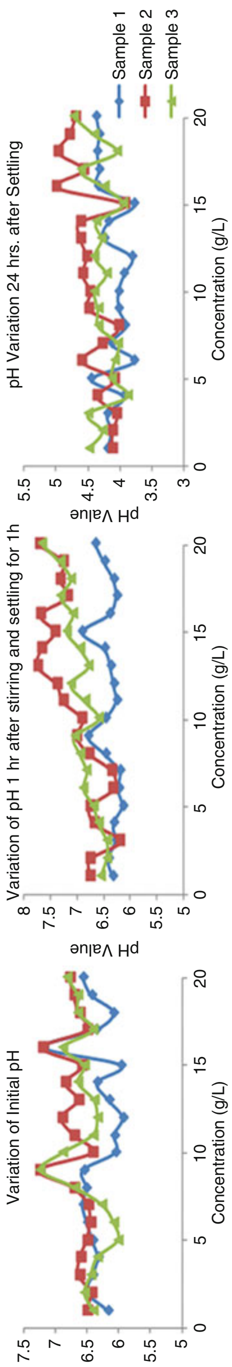


Fig. 8.8 Variation of pH of pond ash-water slurry of different concentrations up to 20 h

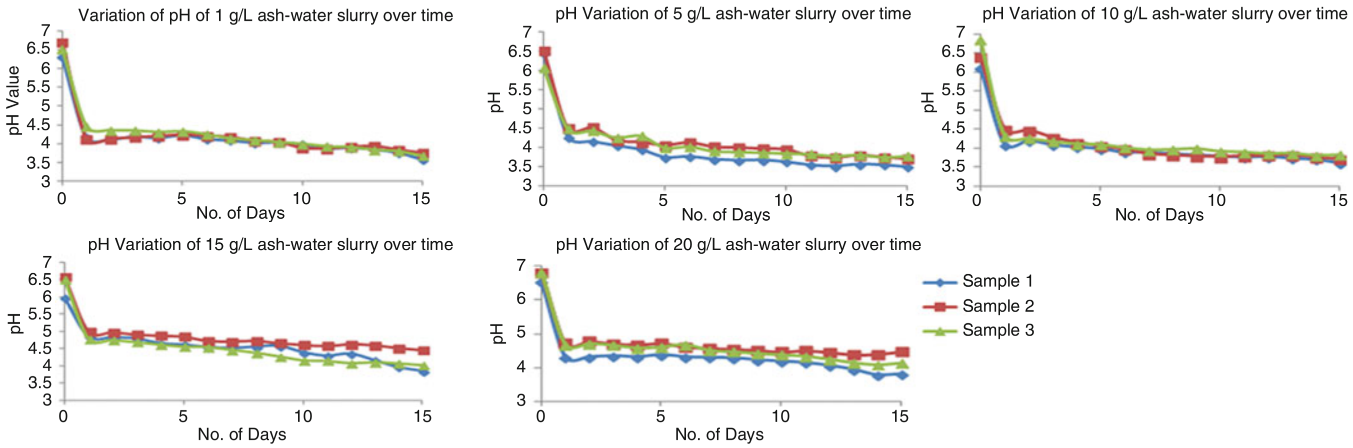


Fig. 8.9 Variation of pH of pond ash-water slurry of different concentrations over 15 days

(iii) Pond ash sample 2 was mostly spherical in shape; samples 1 and 3 consisted of irregularly shaped particles. Distribution of finer particles over the surfaces of larger particles of pond ash samples was observed. EDS spectra of the samples also proved the presence of toxic metals such as Cu, Zn, As and Cd in trace amounts. There are chances of leaching of these surface-bound materials in contact with percolating medium.

(iv) All the samples are unsuitable for use as binder in cement production because of the negligible amount of lime present in all of them. The fly ash present in the pond ash samples was mostly of Class F type.

(v) The pH of pond ash-water slurry was moderately acidic in nature and it turned more acidic over time indicating possible mobilization and contamination of soil, water and river sediments by toxic, heavy metals.

References

Central Electricity Authority, 2014. Report on fly ash generation at coal/lignite based thermal power stations and its utilization in the country for the year 2013–14. CEA, New Delhi. Retrieved from <http://cea.nic.in/reports/others/thermal/tcd/flyash_yearly_201314.pdf> on 1 Oct 2014.

Dasgupta, A. and Paul, S., 2011. Fly Ash and its Impact on Land: A Case Study of Kolaghat Thermal Power Plant, Purba Medinipur, West Bengal. *The Indian Journal of Spatial Sciences*, **2(2)**, 13–20.

Ghosh, P., 2014. Environmental Impacts of Pond Ash dumping: A case study of Kolaghat Thermal Power Plant. M. Tech. Thesis. IIT Kharagpur.

Indian Standard Methods of physical tests for hydraulic cement. IS: 4031 (Part 3) – 1988.

Indian Standard Methods of test for soils. IS: 2720 (Part III/Sec 2) – 1980.

Iyer, R., 2002. The surface chemistry of leaching coal fly ash. *Journal of Hazardous Materials*, **B93(3)**, 321–329.

Izquierdo, M. and Querol, X., 2012. Leaching behaviour of elements from coal combustion fly ash: An overview. *International Journal of Coal Geology*, **94**, 54–66.

Martins, J.V., Hobbs, P.V, Weiss, R.E. and Artaxo, P., 1998. Sphericity and morphology of smoke particles from biomass burning in Brazil. *Journal of Geophysical Research*, **103(D24)**, 51–57.

Neupane, G. and Donahoe, R.J., 2013. Leachability of elements in alkaline and acidic coal fly ash samples during batch and column leaching tests. *Fuel*, **104**, 758–770.

Standard Methods for the Examination of Water and Wastewater. (2005) Published Jointly by APHA, AWWA and WEF in (21st Edition).

Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. ASTM D 698.

Tang, Q., Liu, G., Zhou, C. and Sun, R., 2013. Distribution of trace elements in feed coal and combustion residues from two coal-fired power plants at Huainan, Anhui, China. *Fuel*, **107**, 315–322.

Chapter 9
Leaching Behaviour of Pond Ash

Prasenjit Ghosh and Sudha Goel

1 Introduction

Fly ash and bottom ash are mixed along with water in thermal power plants (TPPs) and the resulting slurry is carried to ash ponds through drains (Shivpuri et al. 2011). This slurry contains trace metals such as As, Cr, Zn, Cd, etc. which are toxic in nature and sometimes radioactive elements such as U, Th, etc. are also present. These metals are highly likely to leach into surrounding soil and groundwater (Mandal and Sengupta 2005) making wet disposal of coal combustion residues (CCRs) a serious environmental concern. On the other hand, fly ash is often dumped in dry state which leads to high levels of suspended particulate matter in the air. As the particle size of the dust varies from sub-micron to microns, it can cause serious respiratory problems. So, fly ash particles can be hazardous in nature and their environmental impacts need to be assessed and mitigated.

Due to the pozzolanic or self-hardening characteristics of CCRs, they can be easily recycled as construction material (Ghosh and Subbarao 1998). Pozzolanic characteristics of a material depend on the presence of lime. If the lime content in CCRs is much less than 7% (Iyer 2002), then there is insufficient bonding between the particles resulting in lack of pozzolanic reaction. Therefore, if CCRs having low lime content are used as structural fill material, they will remain in loose condition and may create leaching and/or dust problems. In that case, stabilization and subsequent utilization of CCRs with proper additives (e.g. gypsum) may be a

---

P. Ghosh (✉)
Centre for Environmental Science and Engineering, Indian Institute of Technology Bombay,
Powai, Mumbai 400076, India
e-mail: ami.prasenjit@gmail.com

S. Goel
Civil Engineering Department, Indian Institute of Technology Kharagpur,
Kharagpur 721302, WB, India

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_9

promising method to reduce leaching and dust problems. High Carbon Content (HCC) fly ash is suitable for using as a reactive medium in permeable sorptive barriers for adsorbing phenols, dyes, herbicides and PCBs from different aqueous solutions containing those pollutants (Konstantinou and Albanis 2000). HCC fly ash has been used as a sorptive medium for treating groundwater containing both organic and inorganic pollutants. So, CCRs can be utilised for different purposes after ensuring that they do not pose any hazard to the environment.

Due to presence of toxic elements in pond ash, it is important to determine their leaching potential in various environmental conditions. Extraction methods are generally applied to simulate such conditions. Various extraction procedures are followed under different controlled conditions (Chang et al. 2009). Parallel extraction, sometimes called Single Step Extraction, is done to measure leached concentrations of different elements from pond ash samples in contact with a particular leaching solution. Sequential Extraction Procedure (SEP) is recommended by the USEPA and has been recently applied to bottom and fly ashes to determine distribution of different elements in them (Huang et al. 2007). It was also used to determine total leachable concentrations and leaching potential of different elements present in the pond ash samples. Toxicity Characteristic Leaching Procedure (TCLP) is generally adopted to determine the hazardous nature of solid wastes under the Resources Conservation and Recycling Act (RCRA) of USEPA.

In this chapter, different extraction procedures are described along with their results. These procedures were applied to investigate the leaching potential of different elements present in the pond ash samples. Parallel extraction, sequential extraction and toxicity characteristic leaching procedure were applied to understand the leaching behaviour of pond ash samples. pH and time dependent leaching behaviour of those elements were also evaluated in batch experiments. Column Leach experiments were conducted using reagent grade water and rain water to compare leaching behaviour of the elements over a period of 7 days.

2 Materials and Methods

The materials used for the leaching experiments were the three pond ash samples and one soil sample collected from Kolaghat and Kharagpur, respectively. These samples were characterized for their physico-chemical properties and are described in Chap. 10. Leaching solutions used for parallel and sequential extractions and TCLP are discussed below in detail. Rain water and reagent grade water were used in pH and time-dependent leaching experiments. Rain water was collected on 15th February, 2014 at Howrah, West Bengal. It was collected in plastic buckets and used for experiments after filtering through 0.45μ Nucleopore Filter Papers.

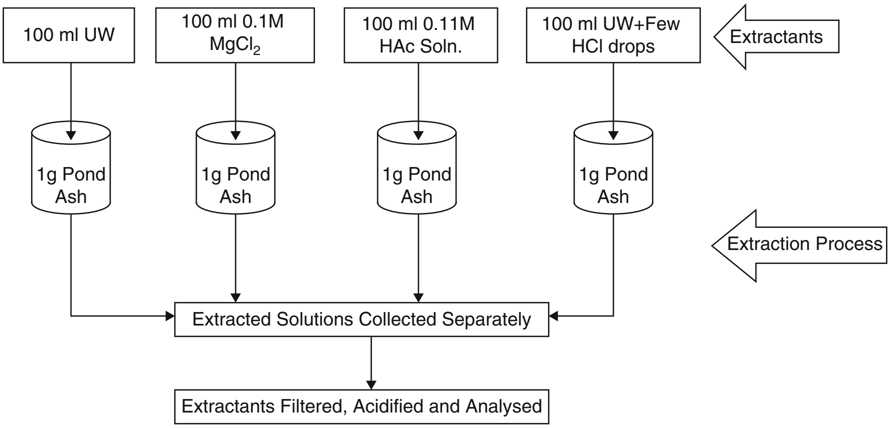


Fig. 9.1 Flowchart showing different steps followed during PEP

2.1 *Parallel Extraction Procedure (PEP)*

Four pond ash samples were exposed to four different leaching (extractant) solutions in the Parallel extraction procedure (PEP) as shown in Fig. 9.1. The four different leaching solutions (one solution applied at a time) are of increasingly aggressive nature. The different leaching solutions used and the corresponding duration of stirring and other details for the current study are compiled in Table 9.1. 1.0 g of oven dried pond ash sample was mixed with 100 mL of leaching solution in 100 mL polyethylene beaker and was agitated by magnetic stir-bar for specified duration given in Table 9.1.

After stirring for specified time periods, each of the solutions was filtered through 0.45μ Whatman Nucleopore filter papers and stored in 100 mL PMP (Polymethylpentene) beakers. So, a constant L/S ratio of 100 was applied to all the pond ash samples. The filtrate samples were analysed by Inductively Coupled Plasma Mass Spectrometer (820 ICP-MS) for analysis of trace elements, and fast sequential atomic absorption spectrophotometer (VARIAN AAS240FS) to determine leached concentrations of Fe and Cu. Cation and anion concentrations of the samples were measured using a Metrohm 761 Compact IC.

2.1.1 Analysis by ICP-MS

The samples were diluted by 1000 times and the diluted solutions were acidified to 2% by adding 70% concentrated nitric acid and stored for trace elements analyses by an inductively coupled plasma mass spectrometer (820 ICP-MS). The calibration standards were blank (reagent grade water), 5 ppb and 500 ppb (mixed

Table 9.1 Details of parallel extraction procedure (PEP)

Steps	Different fractions of leaching	Leaching solutions	Duration of agitation for parallel extraction	Description of leaching solution preparation
1	Water soluble (WS)	Reagent grade water	4 h at ambient temperature	100 ml reagent grade water
2	Ion exchangeable	0.1 M $MgCl_2$	4 h at ambient temperature	2.033 g of $MgCl_2$ in 100 ml reagent grade water
3	Acid soluble at pH ~3 (AS3)	0.11 M acetic acid	24 h at ambient temperature	0.630 ml of acetic acid in 100 ml reagent grade water
4	Acid soluble at pH <4 (AS1)	Few drops of concentrated HCI (70%)	6 h at ambient temperature	Few drops of concentrated HCI addition

Source: Shivpuri et al. (2011)

standards). One 10 ppb mixed standard was run to check on accuracy as well as reproducibility of the measurement. Indium (In) was added as an internal standard.

2.1.2 Analysis by FS-AAS

Fast sequential atomic absorption spectrophotometer (VARIAN AAS240FS) was used to determine leached concentrations of Fe and Cu in the samples. Standards of 1, 2, 3, 4 and 5 ppm of Fe and Cu were run to calibrate the instrument.

2.1.3 Ion Chromatograph (IC) Analysis

Ion chromatograph (IC) analyses of the samples were also performed using a Metrohm 761 Compact IC; in case of IC analyses of cations, the same sample preparation procedure (as mentioned above) was adopted, but in case of IC analyses of anions, the diluted samples were not acidified while the other steps were kept as is. Mixed standards of 5, 10, 20, 40 and 80 ppm were run during cation analyses and mixed standards of 4, 6, 8, 10 and 20 ppm were run during anion analyses to calibrate the instrument.

2.1.4 XRD Analyses of Pond Ash Samples Before and After PEP

Mineralogical composition in the pond ash samples (before and after PEP) were determined by X-Ray Diffraction analyses (XRD) using a panalytical high resolution XRD-I PW 3040/60 diffractometer. Cu K_α radiation was used for the entire experiment. The X-ray beam was made to intersect the samples at glancing angles varying from 10° to 80° (for all the samples). Several angles and intensity data were obtained. Origin Pro 8 and X'Pert Highscore 2012 softwares were used for analyses

Table 9.2 Parameters related to XRD analyses

Parameters	Details/Values
Anode material	Cu
K_α wavelength	1.542 Å
Monochromator used	No
Generator voltage	40 KV
Tube current	30 mA
Scan rate	5.8° 2θ/min
Minimum step size 2θ	0.001°
Measurement programme	XCELERATOR

of XRD data and plotting graphs (diffractograms) between Intensity (counts per second along Y axis) and Position 2θ (degrees along X axis) for respective samples. The general details of the XRD analyses done with all the samples are listed in Table 9.2.

2.2 *Sequential Extraction Procedure (SEP)*

This test was conducted to estimate the cumulative mobility of different elements from pond ash samples in contact with different leaching solutions applied sequentially in order of increasingly aggressive nature. The leaching potentials and total leachable concentrations of different elements present in the three pond ash samples were assessed by Sequential Extraction Procedure (SEP). In this study, a four-step extraction procedure was applied which was modified from that of Tessier et al. (1979). Leaching solutions used were the same as for PEP.

In SEP, initially 1 g of oven dried pond ash was taken and distributed in 10 centrifuge tubes each of 12 mL capacity. Then 100 mL of the first leaching solution i.e., reagent grade water was poured into each centrifuge tube (10 mL in each of the tubes). Then the tubes were kept inside an incubator and agitated @ 30 rpm for same time duration adopted in case of parallel extraction (mentioned in Table 9.1). After agitation, the samples were centrifuged at 10,000 rpm for 10 min. The supernatants were decanted, filtered through 0.45μ Nucleopore filter papers and the filtrates were stored in 100 mL PMP (Polymethylpentene) beakers. Then the filtrate samples were diluted by 1000 times. The diluted solutions were acidified to 2% by adding 70% concentrated nitric acid and stored for trace element analyses using 820 ICP-MS and VARIAN AAS240FS. Remaining leaching solutions were applied in succession to the residual solids obtained from the previous step. The same procedure mentioned above was applied for preserving the supernatant solutions. FS-AAS was performed to measure Fe and Cu concentrations and other elements were detected by ICP-MS. Finally IC analyses of the extracted liquid samples were done for cations and anions. Same standards (as used in case of parallel extraction) were used for calibration of the instruments. Figure 9.2 is a flowchart showing the different stages followed in SEP.

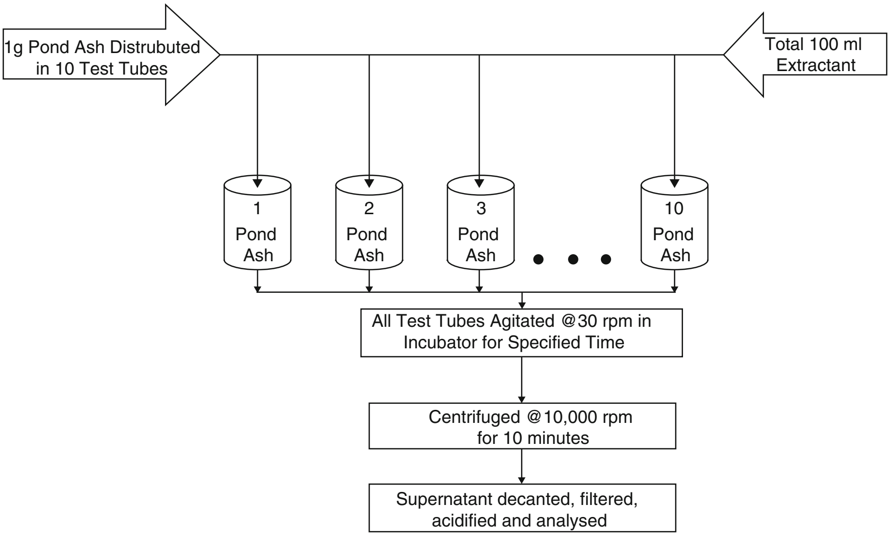


Fig. 9.2 Flowchart showing different steps followed during SEP

2.3 Toxicity Characteristic Leaching Procedure (TCLP)

Toxicity Characteristic Leaching Procedure is a standard method of the U.S. EPA (SW 864 Method 1311) used to assess the toxicity of any hazardous solid waste. Pond ash samples were subjected to TCLP and the results of the leaching test were then compared with the concentrations of various elements prescribed in RCRA lists of Hazardous Wastes with ‘D’ code to determine the hazardous nature of the samples.

Due to non-availability of the reagent ethylene hydroperoxide (or hydroperoxyethane) as mentioned in U.S. EPA procedure, glacial acetic acid and reagent grade water mixture were used as the extraction fluid (Shivpuri et al. 2011). Glacial acetic acid was added drop by drop in 200 mL reagent grade water and pH of the mixture was brought down to 2.88 ± 0.1. For analysis, 1 g of dried pond ash sample was mixed with 40 mL of the extracting solution in a 200 mL conical flask. Then the solution was agitated in a shaking incubator for 18 h at 30 rpm controlled at 30 °C. After that, the supernatant was collected in five numbers of 10 mL centrifuge tubes and the same was centrifuged at 10,000 rpm for 10 min. After centrifugation, the supernatant was filtered through 0.45μ Whatman nucleopore filter paper. Same procedure was applied for all the samples. The filtrate was collected in 100 mL PMP (polymethylpentene) beakers and the pH values of different samples were measured. The filtrates were then diluted by 1000 dilution factor using reagent grade water and the diluted solutions were acidified to 2% by adding 70% concentrated nitric acid and were stored for trace element analyses using 820 ICP-MS and VARIAN AAS240FS. IC analyses were also done using a Metrohm 761 Compact IC following the same procedure as discussed in Parallel

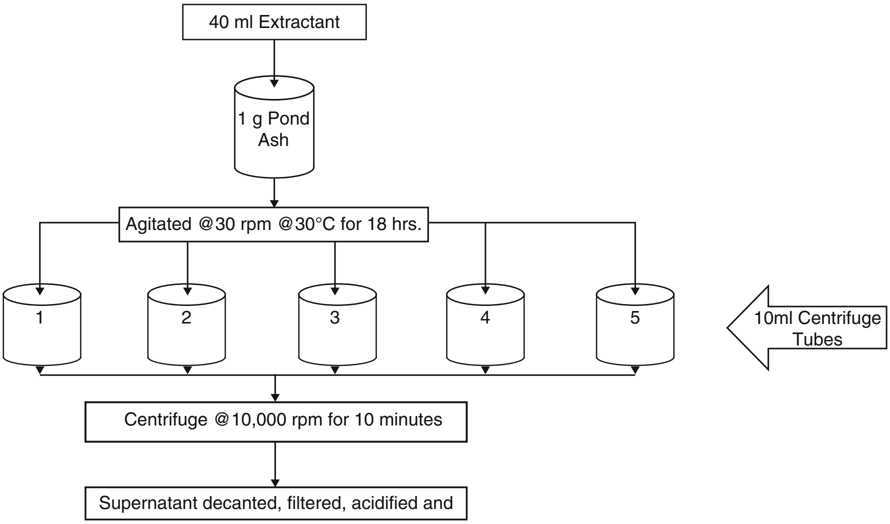


Fig. 9.3 Flowchart showing different steps followed during TCLP

Extraction Procedure. Same standards (as used in parallel extraction) were used for calibration of the instruments. Figure 9.3 is a flowchart showing different stages of sample preparation during TCLP.

2.4 pH Dependent Leaching Behaviour of Pond Ash

A pH dependent leaching test on pond ash samples was conducted to investigate the leaching behaviour of different elements present in pond ash samples under different pH conditions. SW-846 Method 1313 was followed to perform the test. The test results can be used for geochemical modelling to identify the mechanism (s) controlling leaching of elements.

The method consisted of six parallel extractions of pond ash materials in dilute acid, dilute base and reagent grade water. At first, the pond ash samples were sieved through 2 mm IS sieve and the finer fraction was oven dried for 24 h at 105 °C in a hot air oven. The dried pond ash samples were taken for the experiment. The schedule of acid and base additions was formulated from pre-test titration curves obtained after adding the same reagents to the pond ash samples to yield pH values varying from 1 to 14. A five-point titration curve was drawn for each of the pond ash samples from the obtained data of milliequivalents of reagent (dilute acid, dilute base and reagent grade water) added and pH of solution (Fig. 9.4). From the titration curves, the quantity of reagents needed to be added could be found for controlling the pH of the samples. The acid and base used for preparing reagents for titration were 70% concentrated HNO_3 and pellets of KOH. Reagent grade water

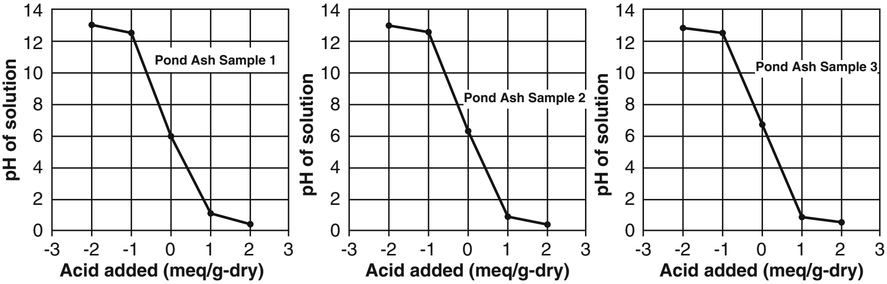


Fig. 9.4 Titration curves of three pond ash samples

was used for diluting them to 2N and 1N HNO_3 and KOH, respectively which were then used as reagents for the experiment.

Six target pH points (varying from 1 to 14) were chosen and the required amount of reagent addition (in meq/g dry weight of pond ash) was determined from the titration curves for the three pond ash samples. Six numbers of 250 mL glass conical flasks were used for each of the pond ash samples for adjusting six different eluent pHs. Liquid to solid ratio of 10 mL/g of dry pond ash was maintained throughout the test. After the addition of titrants, the mouths of the conical flasks were covered with Parafilm and were kept inside a shaking incubator to agitate the samples at 30 ± 2 rpm at room temperature (28 ± 0.5 °C) for 12 ± 1 h. Then the samples were taken out and were allowed to stand for 20 ± 5 min. The supernatant was filtered through 0.45μ Nucleopore filter paper and the filtrate was collected in 100 mL PMP beakers. They were then diluted and acidified following the same procedure that was adopted in case of parallel extraction. Same standards (as used in case of parallel extraction) were used for calibration of the instruments.

2.5 *Time Dependent Leaching Behaviour of Pond Ash*

A study on time dependent leaching behaviour of pond ash samples was carried out to understand the leaching behaviour of different elements with respect to time. A time period of seven days was chosen for performing the study. At first, 21 numbers of 250 mL glass conical flasks were taken and rinsed with tap water, then with acid water and finally with reagent grade water to avoid any contamination. Then they were kept in oven an overnight at 105 °C for drying and the dried samples were taken for the test. 10 gm of pond ash sample 1 was taken in each of seven conical flasks and in similar way 10 gm of pond ash samples 2 and 3 were taken in remaining fourteen conical flasks. Then in each of them 100 mL of reagent grade water was poured to maintain a constant L/S ratio of 10 mL/g in all of the conical flasks. Then the flasks were covered with Parafilm to avoid any contamination from outside. They were kept inside a shaking incubator. The samples were shaken at 120 rpm and maintained at 28 ± 0.5 °C. The samples were kept in the shaking incubator for seven days and on each day, three conical flasks (one of each pond ash sample) were taken out from the incubator. After taking out the flasks, they were kept undisturbed for 30 min to allow the suspended ash particles settle down. The supernatant was then filtered through 0.45μ Nucleopore filter paper and the filtrate was collected in 100 mL PMP (Polymethylpentene) beakers. So in seven days, total twenty one samples were collected. The samples were then diluted, acidified (immediately after collecting them) and stored for analyses by ICP-MS, FS-AAS and IC following the same procedure adopted in parallel extraction. Same standards (as used in case of parallel extraction) were used for calibration of the instruments.

2.6 Column Leach Tests

Column Leach Tests (CLTs) were performed on pond ash-soil assemblies to obtain more realistic results about leaching behaviours of different elements present in pond ash. OECD guidelines and ASTM D4874-95 were followed for performing the tests although in some cases (e.g., application of influent leaching solution, collection of leachate, etc.) the procedures were modified. One acrylic column (64 cm long, 9.025 cm internal diameter and 4 mm thick) was used for the tests. The column was operated in a down-flow mode using a peristaltic pump on the influent line to maintain constant inflow rate to the column. The influent line consisted of one Teflon tubing connecting a PTFE bottle filled with the feed solution to the fitting at the top of the column. One stainless steel perforated plate was attached at the bottom of the column to maintain uniformity in leachate sample collection. At the top of the column, one perforated polyethylene plate was also attached to ensure uniform distribution of the influent solution in the column. A schematic of the column leach experimental setup is shown in Fig. 9.5. Both reagent grade water (pH ~7.26) and rain water (pH ~6.54) were used as leaching solutions for performing the tests. The inflow rate was maintained at 180 mL/h to simulate rainfall intensity in the study area (http://www.imd.gov.in/). The inflow rate adopted was on the higher side of the average rainfall intensity representing precipitation on a typical rainy day.

The column was fitted with a stainless steel porous plate at the bottom and a coarse filter paper was kept at the top of the steel plate to prevent clogging of the porous plate by soil particles. Equal amounts of soil (background soil) and pond ash (three pond ash samples were tested separately in three experiments) were added to the column (400 g each); pond ash samples were placed over soil samples. Both samples were air dried for 24 hours at 105 °C and then sieved through a 4.75 mm IS sieve before using the same in column leach tests. After pouring 400 g soil sample inside the column, hand compaction was done using a plastic rod to avoid contamination. After pouring pond ash sample again, the pond ash-soil assembly was compacted. Initially, the pond ash-soil assembly was saturated by adding 100 mL of the leaching solutions at 180 mL/h using peristaltic pump. Saturation period varied from 5 to 7 h. After saturating the column media, 250 mL of leaching

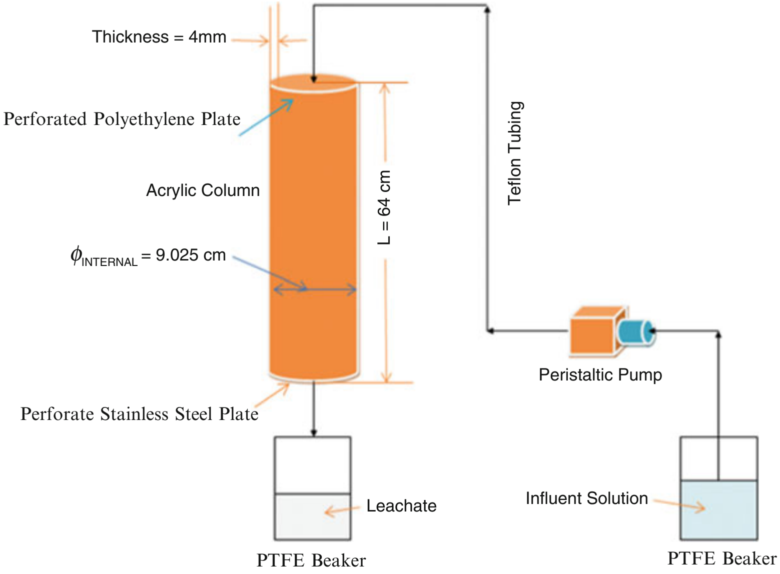


Fig. 9.5 Experimental setup of column leach test

solution was applied to the column maintaining the same inflow rate. The same L/S ratio was used throughout the experiment. Peristaltic pump was stopped when all the influent solution went into the column. One PTFE beaker was kept at the bottom of the column to collect the leachate sample. All the leachate samples of the 1st day (for all the pond ash-soil assemblies) were collected within 6-8 h after the pump was stopped. 250 mL of leaching solution was added again after collecting 1st day's leachate sample.

Same procedure was followed to collect leachate samples on 2nd day. The column was acid-washed before changing the pond ash-soil assembly in the column. The PTFE bottles and beakers were acid-washed before conducting each day's experiment. The leachate samples were collected daily and pH of the same was measured. Then they were filtered and the filtrates were diluted, acidified and stored in 100 mL PMP beakers at 4 °C in refrigerator (following the same procedure that was done in parallel extraction). All the samples were analysed by ICP-MS, FS-AAS and IC following the same procedure adopted for parallel extraction. Same standards (as used in parallel extraction) were used for calibration of the instruments.

Experiments were conducted over 1 week with each pond ash sample and each leaching solution. The purpose of using two types of leaching solutions (rain water and reagent grade water) was to identify changes in leaching behaviour of different elements in contact with actual rain water that occurs in the field in comparison with reagent grade water.

3 Results and Discussion

Results of parallel and sequential extraction methods and the column leach tests are discussed in this section.

3.1 *Parallel Extraction of Pond Ash Samples*

Average concentrations of each element calculated for the three pond ash samples and analysed by ICP-MS and FS AAS are shown in Table 9.3. All elements in Table 9.3 were sorted in order of their leached concentrations in the extractant solutions. It was observed that leaching of different elements from the samples varied with change in pH. In general, as pH decreased the solubility of the elements increased. The only exceptions observed were for Ti, Ag and Eu with their lowest solubilities at around pH 6 (IE), and Cd and Pb had their highest solubilities at pH 3. Other exceptions like Na and As concentrations were too close to the detection limit of ICP-MS method.

Leachate concentrations of the different elements are categorized based on their concentrations:

(a) >10,000 mg/kg: Ti and Mo had concentrations greater than 10,000 mg/kg in the extractant with pH 1.
(b) >1000 and <10,000 mg/kg: Mo had concentrations greater than 1,000 mg/kg in all four extractants while Ti dissolved to a major extent at pH 3 and greater.
(c) >100 and <1,000 mg/kg: Al, Zn and Pb were found in concentrations ranging from 100 to 1000 mg/kg when the extractant had pH 3 or less.
(d) >10 and <100 mg/kg: Al, Zn, Ni, V, Ba, La, Pb, Ag, Rb, Cr, Sc, Fe, Co, Pr and Ce were found in the different extractant solutions with concentrations ranging from 10 to 100 mg/kg.

All the Lanthanides and Actinides leached the highest in AS1 fraction, pH = 1. Other elements were detected in relatively higher concentrations in both acid soluble fractions (AS3 and AS1) compared to that detected in other fractions. Toxic elements in the water soluble fractions leached in higher concentrations than the WHO prescribed limits for drinking water. Based on these results, there is a high chance of contamination of soil and groundwater surrounding the ash ponds due to leaching of toxic and heavy metals as well as some of the radioactive elements.

3.1.1 XRD Analyses of Pond Ash Samples Before and After Parallel Extraction

X-ray diffractograms of different pond ash samples before and after parallel extraction are shown in Fig. 9.6. Figure 9.6a–c represent XRD patterns of pond

Table 9.3 Results of ICP-MS and FS AAS analyses after parallel extraction in mg/kg

	Water soluble			Ion exchangeable			Acid soluble – pH 3			Acid soluble – pH 1	
Elements	Average	SD		Average	SD		Average	SD		Average	SD
Mo	1453.488	440.253	Mo	2276.159	1039.033	Mo	5124.056	379.843	Ti	22859.263	2472.570
Ti	422.601	59.391	Ti	153.723	27.512	Ti	1378.598	112.012	Mo	13505.793	7399.186
Al	39.783	21.407	Al	60.843	24.082	Pb	143.309	71.117	Al	215.340	58.090
Ba	30.520	19.693	Pb	58.378	18.837	Al	137.953	49.881	Zn	103.043	9.634
Ni	6.924	2.338	Ba	32.238	20.732	Ni	45.045	19.989	Ni	76.860	16.992
Pb	6.894	4.647	Zn	17.683	5.085	Ba	43.069	18.307	V	71.602	48.171
Rb	6.311	1.816	Ni	8.610	5.213	Zn	39.461	12.912	Ba	50.762	21.475
Cr	6.100	1.939	Cr	8.557	0.818	V	35.507	29.987	La	45.179	14.930
Zn	5.721	3.137	Rb	8.331	4.309	La	22.748	16.596	Pb	41.610	35.793
Ag	4.663	1.311	V	4.334	2.778	Rb	17.824	5.269	Ag	25.482	12.263
V	3.883	2.303	Ag	3.731	0.863	Cr	14.797	3.073	Rb	24.770	9.183
Na	2.647	1.265	Ce	3.501	3.092	Sc	9.582	4.159	Cr	21.823	4.875
Sc	2.417	0.387	Sc	2.910	0.801	Fe	7.071	2.588	Sc	21.594	4.497
As	2.048	1.306	Sr	2.085	0.717	Pr	5.884	4.366	Fe	15.044	2.459
Ce	1.868	1.180	Na	2.075	0.712	Ce	5.777	3.321	Co	11.897	3.684
Fe	1.437	0.161	As	2.049	1.405	Ag	5.289	1.335	Pr	10.756	4.836
Sr	1.374	0.597	Fe	1.598	0.246	Sm	4.757	3.444	Ce	10.299	6.556
Ta	0.853	0.083	Ta	1.009	0.139	Gd	4.705	3.977	Gd	9.674	4.239
Nd	0.559	0.200	Co	0.749	0.644	Co	4.542	4.730	Ta	9.125	5.608

Y	0.492	0.359	Li	0.684	0.518	Dy	3.626	3.361	Sm	8.861	3.494
La	0.453	0.300	Nd	0.632	0.306	Na	2.772	2.234	Dy	7.191	1.711
Gd	0.395	0.541	La	0.561	0.184	Ta	2.239	0.727	Y	4.576	3.023
Ir	0.359	0.184	Y	0.458	0.062	Y	2.177	1.218	Sr	4.421	1.331
Li	0.311	0.273	Ir	0.414	0.210	Nd	2.144	1.525	Nd	4.054	1.252
Co	0.279	0.169	Gd	0.386	0.396	Sr	2.057	0.898	Er	3.411	1.054
Cd	0.267	0.105	Cu	0.316	0.179	Er	1.937	1.478	Yb	2.541	0.685
Eu	0.209	0.185	Cd	0.249	0.006	Cd	1.491	0.324	Eu	2.435	0.702
Cu	0.142	0.033	Pr	0.196	0.165	Eu	1.050	0.637	Na	1.723	1.348
Pr	0.091	0.059	Eu	0.176	0.141	Yb	0.993	0.770	Tb	1.533	0.476
Dy	0.064	0.022	Sm	0.123	0.022	Tb	0.652	0.478	Ir	1.355	0.304
Sm	0.055	0.033	Dy	0.103	0.083	Ir	0.642	0.186	Ho	1.327	0.607
U	0.049	0.025	Yb	0.091	0.108	As	0.489	0.278	Cd	0.926	0.108
Th	0.046	0.036	U	0.083	0.061	Cu	0.484	0.352	Cu	0.716	0.635
Yb	0.021	0.007	Th	0.068	0.026	Ho	0.425	0.551	As	0.469	0.323
Er	0.020	0.014	Tb	0.036	0.042	Li	0.352	0.239	Tm	0.377	0.062
Tb	0.018	0.010	Er	0.022	0.022	Tm	0.183	0.129	U	0.294	0.027
Ho	0.010	0.008	Ho	0.016	0.010	U	0.149	0.032	Lu	0.275	0.060
Lu	0.004	0.002	Tm	0.004	0.001	Th	0.139	0.024	Li	0.270	0.126
Tm	0.004	0.001	Lu	0.003	0.001	Lu	0.024	0.008	Th	0.249	0.038

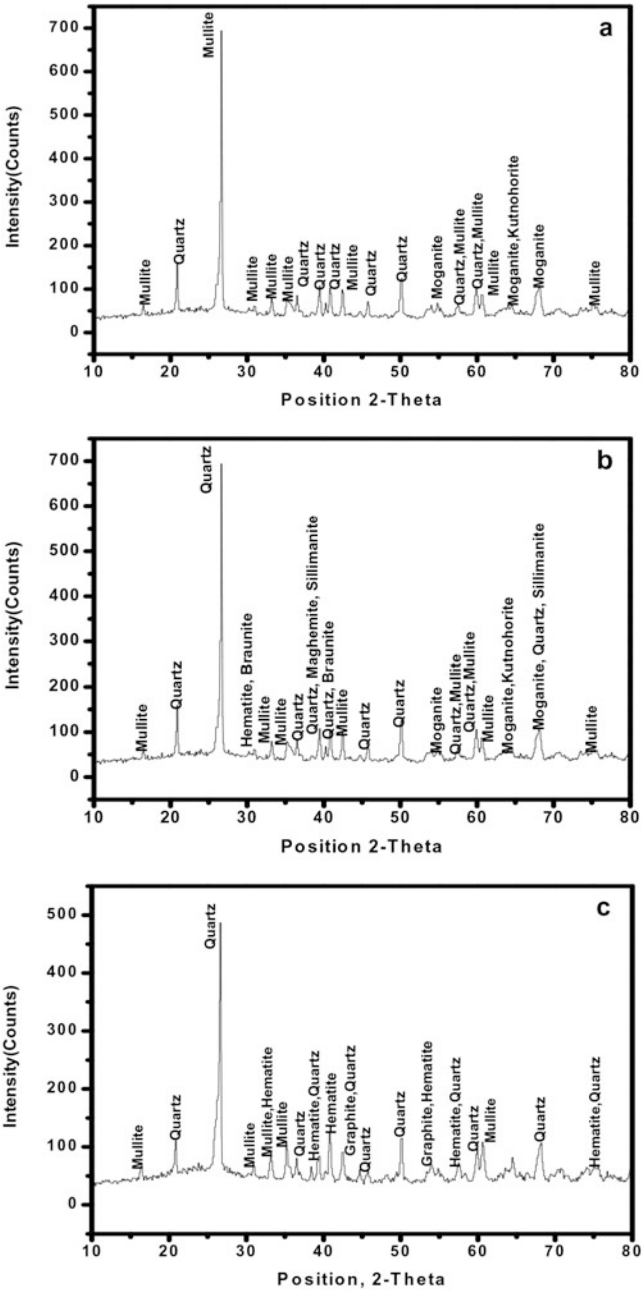


Fig. 9.6 (**a**–**o**) XRD patterns of pond ash samples before and after parallel extraction
Note: Mullite – $3Al_2O_3.2SiO_2$; Mullite syn. – $Al_{2.4}Si_{0.6}O_{4.8}$; Quartz – SiO_2; Hematite – Fe_2O_3; Graphite – C; Braunite – $Mn^{2+}Mn^{3+}{}_6[O_8|SiO_4]$; Maghemite – ($Fe_2O_3$, γ-Fe_2O_3); Sillimanite – Al_2SiO_5; Moganite – SiO_2; Kutnohorite – $Ca(Mn^{2+}, Mg, Fe^{2+})(CO_3)_2$; Berlinite – $Al(PO_4)$; Senaite – $PbTi_{10}Fe^{2+}{}_7Mn^{2+}{}_4O_{38}$; Bavenite – $Ca_{4.1}Be_{2.9}Al_{1.2}Si_{9.2}O_{26}(OH)_2$; Sanbornite – Ba (Si_2O_5); Cryolithionite – $Na_3Li_3Al_2F_{12}$; Sidorenkite – $Na_3Mn^{2+}(PO_4)(CO_3)$; Tochilinite – $6Fe_{0.9}S_{0.5}(Mg,Fe^{2+})(OH)_2$; Cuprite – Cu_2O; Hercynite – $Fe^{2+}Al_2O_4$ and Leucite – $KAl(Si_2O_6)$

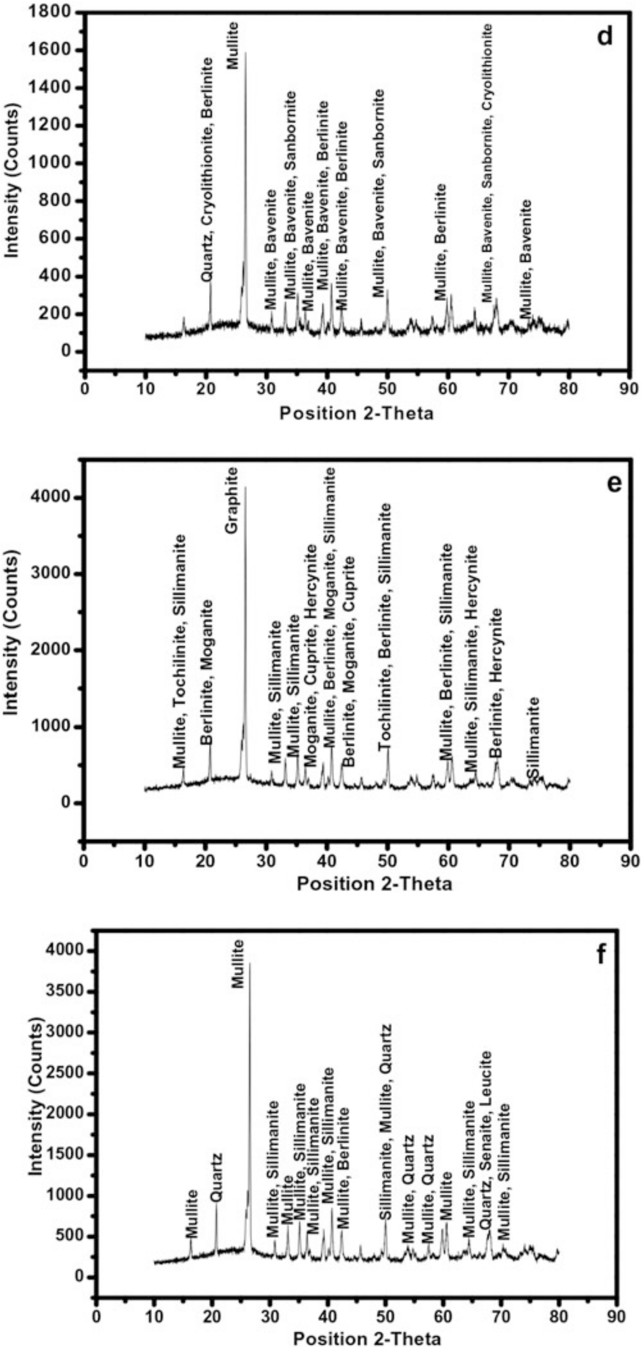


Fig. 9.6 (continued)

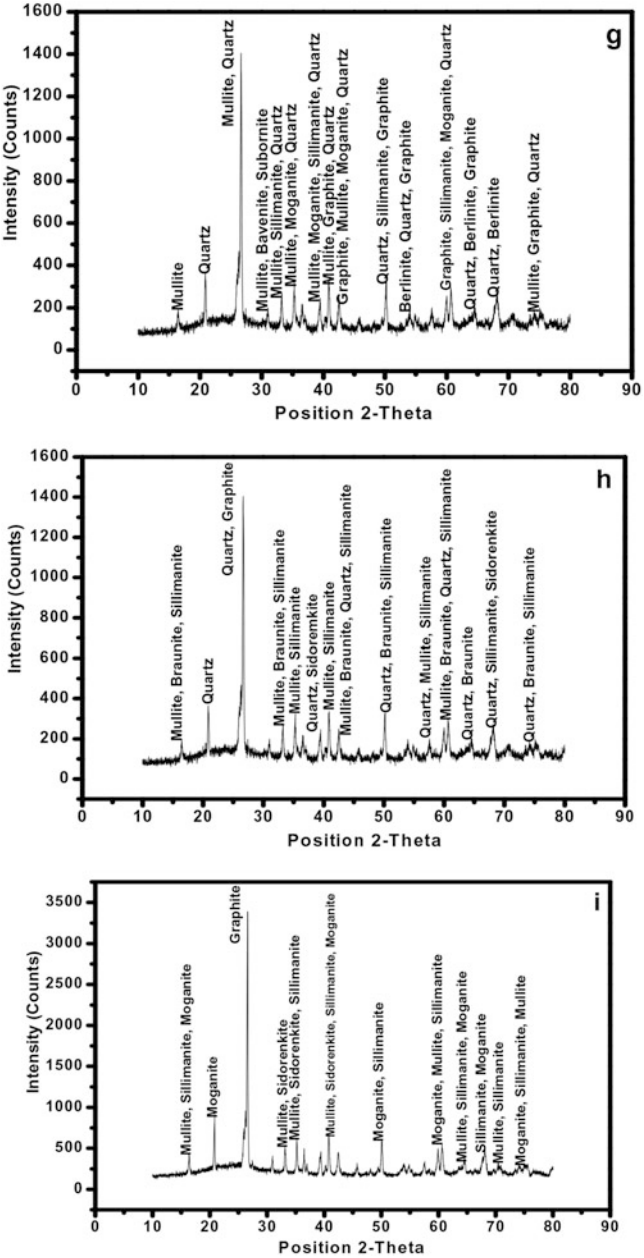


Fig. 9.6 (continued)

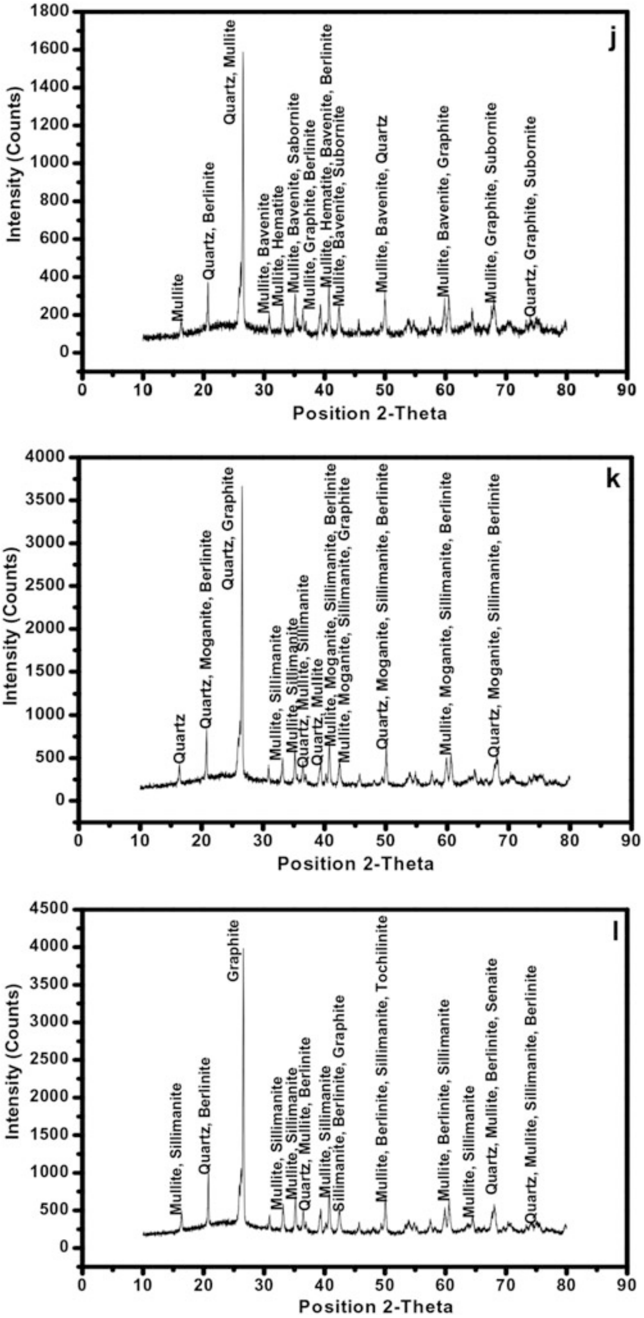


Fig. 9.6 (continued)

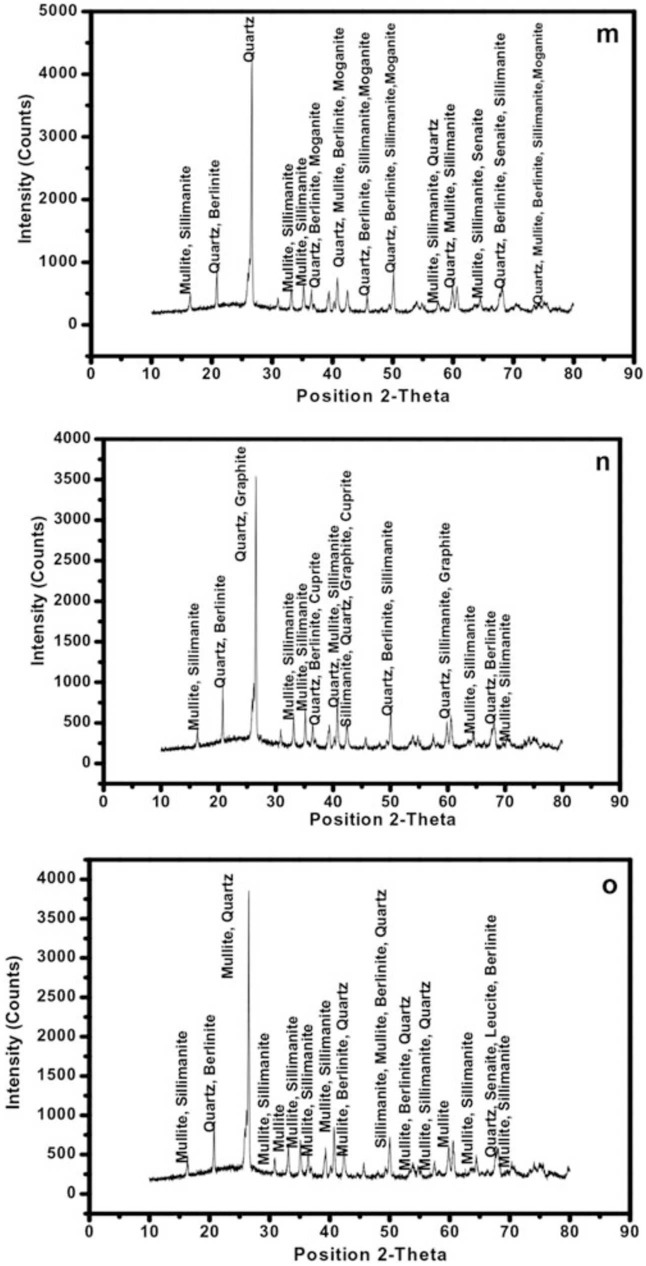


Fig. 9.6 (continued)

ash samples 1, 2 and 3 respectively before leaching; 9.6 (d to f) represent XRD patterns of the samples after leaching with Ultrapure Water (samples 1, 2 and 3 respectively); 9.6 (g to i) represent XRD patterns of the samples after leaching with Ultrapure Water and $MgCl_2$ (samples 1, 2 and 3 respectively); 9.6 (j to l) represent XRD patterns of the samples after leaching with Ultrapure Water and HAc at $pH \approx 3$ (samples 1, 2 and 3 respectively); 9.6 (m to o) represent XRD patterns of the samples after leaching with Ultrapure Water and HCl at $pH < 1$ (samples 1, 2 and 3 respectively).

Different major and minor minerals found in pond ash sample 1 (before leaching) were Mullite, Quartz, Moganite and Kutnohorite; Quartz, Hematite, Braunite, Maghemite and Sillimanite were found in pond ash sample 2 and Mullite, Quartz, Graphite and Hematite were found in pond ash sample 3. The residual samples after PEP were also analysed to identify whether there is any alteration in mineralogical composition compared to the original solid (before leaching) samples. In pond ash sample 1, Mullite was present as the strongest peak which was also observed in case of residual sample obtained from WS fraction. In case of IE and AS3 residual solids both Mullite and Quartz had the strongest peaks; but the strongest peak in case of AS1 residual solids changed to Quartz. In pond ash sample 2, Quartz was present as the strongest peak which changed to Graphite in WS residual solids. In other residual solids obtained from sample 2, strongest peaks consisted of both Quartz and Graphite. In pond ash sample 3, Quartz was present as the strongest peak which changed to Graphite in IE and AS3 residual solids. Strongest peaks in case of WS and AS1 residual solids consisted of both Mullite and Quartz. Other minor peak minerals also changed in case of residual solids compared to the original solids. Some new minerals namely Berlinite, Bavenite, Sanbornite, Cuprite and Senaite were present in the residual solids which could not be detected in the original solids. The results show that leaching with different extractants changed the mineralogical composition of the samples to some extent.

3.2 Sequential Extraction Procedure (SEP)

Total leached concentrations of each element after SEP are summarized in Table 9.4 and Relative leaching of different extractable fractions (in %) of various elements in contact with different leaching solutions after SEP are shown in Figure 9.7. It was observed that leaching potentials of different elements from the pond ash samples varied with change in pH. Na and Mo were mostly water soluble. Li and Ni mostly leached in ion exchangeable fraction. Arsenic could be traced mostly in water soluble and ion exchangeable fractions. Leaching potentials of toxic elements such as Cr, Zn, Pb, Cd and Cu increased with decrease in pH of the leaching solutions (except arsenic) and they were mostly acid soluble (AS3 and AS1 fractions). Leaching of lanthanides and actinides was maximum in AS1 fraction. Other elements were detected in high concentrations in both acid soluble fractions (AS3 and AS1). Sequential extraction results also gave the total leached

Table 9.4 Leached concentrations of elements (mg/kg) after SEP

Elements	PA-I	PA-II	PA-III	Average	SD
Ti	22717.12	24294.95	26293.59	24435.22	1792.36
Mo	19022.00	22064.00	26024.00	22370.00	3511.02
Al	313.55	579.28	533.60	475.48	142.08
Pb	393.67	191.25	182.09	255.67	119.60
Ba	276.89	123.50	111.02	170.47	92.37
Zn	137.22	150.25	197.06	161.51	31.47
Ni	106.73	147.03	185.91	146.56	39.59
V	74.07	197.11	57.99	109.72	76.10
La	34.03	95.00	82.51	70.51	32.21
Rb	56.15	40.60	74.37	57.04	16.90
Cr	59.92	61.94	49.16	57.01	6.87
Ag	58.90	29.23	37.84	41.99	15.26
Sc	33.30	38.20	45.87	39.12	6.34
Co	12.72	24.47	18.70	18.63	5.88
Fe	18.00	15.00	17.00	16.67	1.53
Pr	7.09	21.21	21.68	16.66	8.29
Ce	5.73	18.25	25.34	16.44	9.93
Sm	7.11	21.87	16.47	15.15	7.47
Sr	14.84	7.75	19.15	13.91	5.76
Na	12.42	13.89	9.57	11.96	2.20
Ta	8.82	5.39	17.37	10.53	6.17
Gd	7.10	20.04	1.53	9.56	9.50
Y	9.17	3.14	11.51	7.94	4.32
Nd	2.31	8.42	9.53	6.75	3.89
As	4.84	5.40	7.08	5.77	1.17
Er	3.06	8.33	5.13	5.51	2.66
Yb	2.03	6.24	4.08	4.12	2.11
Li	5.88	2.82	3.46	4.05	1.61
Eu	3.10	2.49	5.73	3.77	1.72
Dy	6.09	2.59	1.25	3.31	2.50
Cd	2.25	3.48	2.95	2.89	0.62
Ir	2.68	2.70	2.68	2.69	0.01
Tb	1.04	4.13	2.06	2.41	1.57
Ho	1.04	3.12	1.05	1.74	1.20
Cu	0.85	0.87	0.85	0.86	0.01
Tm	0.43	0.74	0.71	0.63	0.17
U	0.44	0.53	0.36	0.44	0.09
Lu	0.36	0.46	0.33	0.38	0.07
Th	0.38	0.39	0.37	0.38	0.01

Note: Fe and Cu analysed by FAAS

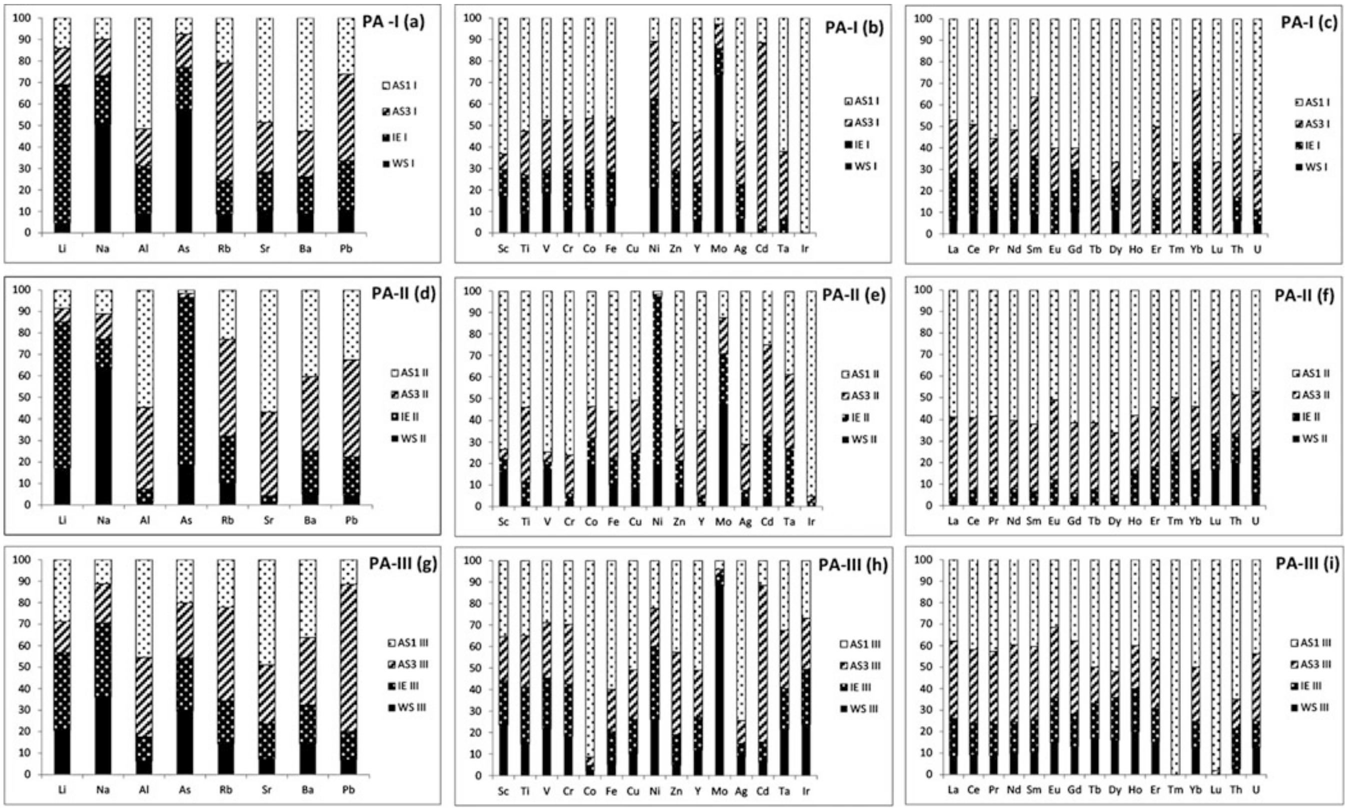


Fig. 9.7 Relative leaching of different extractable fractions (in %) of different elements in contact with various leaching solutions after SEP

concentrations of elements from the pond ash samples as shown in Table 9.4. Based on average concentrations for the three samples tested, the elements are arranged in order from highest to lowest concentrations in the table. Elements such as Ti and Mo leached in concentrations $>$10,000 mg/kg. Elements like Al, Pb, Ba, Zn, Ni and V were in excess of 100 mg/kg of the dry pond ash samples. Total leachable content of toxic elements were high for Pb (180–400 mg/kg), moderately high for Cr (49–62 mg/kg) and low for Cd, Cu and As (0.8–8 mg/kg). Radioactive elements like Th and U could also be detected (0.2–0.6 mg/kg) in all the fractions extracted from the pond ash samples. Other elements leached from pond ash in concentrations varying from few mg/kg to few hundred mg/kg of pond ash samples.

3.3 Toxicity Characteristic Leaching Procedure (TCLP)

Elements extracted by TCLP are summarized in Table 9.5. During TCLP and similar to PEP and SEP, Mo and Ti were extracted to the greatest extent from all three samples. However, the concentrations were in excess of 1000 mg/kg of dry pond ash samples. Al and Pb leached in high concentrations in excess of hundred mg/kg of dry pond ash samples. Elements leached in excess of 10 mg/kg were Ba, Ni, Zn, V, Rb, Cr, Y and Sc. Other toxic elements like Co and Cd leached in concentrations greater than 1 ppm to less than 10 ppm. Radioactive elements like Th and U along with elements like As were detected in all the fractions extracted from the pond ash samples but were less than 1 ppm in concentration.

According to USEPA's Resource Conservation and Recovery Act (RCRA), eight toxic heavy metals (RCRA-8) are listed and considered for assessing whether a material is hazardous after performing TCLP on the same. These metals are shown in Table 9.6 along with their RCRA regulatory limits. Exceedence of the limits for even one of these metals is sufficient to define a material as hazardous. Hg could not be measured by ICP-MS and is not included in the table. Comparing the data listed in Table 9.5, it can be concluded that Ag, Pb and Cr were present in the extracted solutions (from the three pond ash samples) at concentrations far exceeding the regulatory levels. Ba and As leached within the regulatory standards while Cd leached just above the regulatory standard level. So, the pond ash samples can be classified as hazardous material.

3.3.1 IC Analysis of Samples Obtained After PEP, SEP and TCLP

Results of IC analyses of the samples obtained after PEP, SEP and TCLP are shown in Figs. 9.8 and 9.9. Variable leaching behaviours of different cations and anions were observed. Four cations namely NH_4^+, K^+, Ca^{2+} and Mg^{2+} and seven anions namely F^-, Cl^-, NO^{2-}, Br^-, NO^{3-}, PO_4^{3-} and SO_4^{2-} were analysed by IC.

Table 9.5 Concentrations of different elements (ppm or mg/L) after TCLP analysis

Elements	PA- I	PA- II	PA- III	Average	SD
Mo	4283.15	5341.4	4971.813	4865.45	537.08
Ti	1525.59	1320	1533.58	1459.72	121.07
Pb	217.229	96.934	117.897	144.02	64.26
Al	94.78	125.84	184.25	134.96	45.43
Ba	61.911	44.13	28.491	44.84	16.72
Ni	28.4	43.676	56.82	42.97	14.22
Zn	30.713	37.708	50.626	39.68	10.10
V	27.279	38.409	19.915	28.53	9.31
Rb	18.065	14.394	19.035	17.16	2.45
Cr	15.122	12.545	16.456	14.71	1.99
Y	23.151	14.37	3.741	13.75	9.72
Sc	5.445	13.404	12.478	10.44	4.35
Fe	10.25	8.122	4.7	7.69	2.80
La	3.172	7.133	9.091	6.47	3.02
Ce	3.634	5.477	9.6	6.24	3.05
Pr	0.464	8.658	8.897	6.01	4.80
Ag	6.096	5.939	3.846	5.29	1.26
Gd	0.155	8.376	7.102	5.21	4.42
Co	2.01	9.874	1.848	4.58	4.59
Sm	0.894	7.051	5.549	4.50	3.21
Dy	0.0625	6.756	4.28	3.70	3.38
Na	2.219	1.644	5.519	3.13	2.09
Sr	2.991	2.671	2.351	2.67	0.32
Ta	2.65	2.23	1.845	2.24	0.40
Er	0.673	3.413	2.589	2.23	1.41
Nd	0.549	3.154	2.402	2.04	1.34
Eu	0.44	2.68	1.431	1.52	1.12
Cd	1.441	1.621	1.031	1.36	0.30
Tb	0.381	1.452	0.973	0.94	0.54
Yb	0.137	1.255	1.366	0.92	0.68
As	0.911	0.642	0.943	0.83	0.17
Ir	0.785	0.665	0.5925	0.68	0.10
Ho	0.271	1.367	0.022	0.55	0.72
Li	0.606	0.594	0.207	0.47	0.23
Cu	0.215	0.252	0.825	0.43	0.34
Tm	0.0483	0.457	0.269	0.26	0.20
Th	0.247	0.175	0.163	0.20	0.05
U	0.133	0.137	0.172	0.15	0.02
Lu	0.0244	0.0248	0.0359	0.03	0.01

Note: Fe and Cu analysed by FAAS

Table 9.6 Comparison of data obtained from TCLP and regulatory level

Constituents	TCLP (PA-I) mg/L	TCLP (PA-II) mg/L	TCLP (PA-III) mg/L	Regulatory level mg/L
As	0.911	0.642	0.143	5
Ba	61.911	44.13	28.491	100
Cd	1.441	1.621	1.031	1
Cr	15.122	12.545	16.456	5
Pb	2170.229	960.934	1437.897	5
Se	NA	NA	NA	1
Ag	77.096	57.939	97.846	5

Note: NA not analysed
Source: http://www.epa.gov/region2/children/k12/english/art-3of5.pdf

Cations Bar graphs of cations present in PEP extractants show that in general all cations were extracted to some extent in the ion exchangeable fraction. Ca^{2+} was found to be in high concentrations in AS3 fraction as well. IC analyses results of cations present in TCLP extractants showed that K^{+} could not be traced in any of the samples and other cations leached in very less amounts during TCLP.

Anions In case of IE and AS1 fractions, Cl^{-} ion concentrations were not reported due to interference from Cl^{-} ions present in extracting solution. Comparing all the fractions, it can be concluded that IE fraction was responsible for leaching of almost all the anions analysed in significant concentrations.

IC analyses results of the samples obtained after SEP showed quite similar leaching trends as parallel extraction. The difference was basically in the measured concentrations of cations and anions; in case of sequential extraction, measured concentrations were higher than those obtained in parallel extraction. In case of IE and AS1 fractions, Cl^{-} ion concentrations were not reported due to interference from Cl^{-} ions present in extracting solution. In case of anions, F^{-} was found to leach the highest. NO^{2-} could not be detected in any of the samples. Other anions leached in moderate amounts.

3.4 pH Dependent Leaching Behaviour of Pond Ash

Figures 9.10, 9.11 and 9.12 show leaching trends of different elements from pond ash samples under different pH conditions. Figure 9.10 shows leaching trends of some selected alkali metals, alkaline earth metals, post-transition metals and metalloids. Li, Na and Rb belong to the alkali metals group in the Periodic Table. Leaching trends of these metals were considerably different from each other. Li leached highest in the low pH range. In case of Na, maximum leaching occurred within pH range of 6–8 and in case of Rb, maximum leaching occurred in high pH, i.e., alkaline range. Sr and Ba belong to alkaline earth metals group in the Periodic Table. Sr leached highest in the low pH range. Leaching of the same was

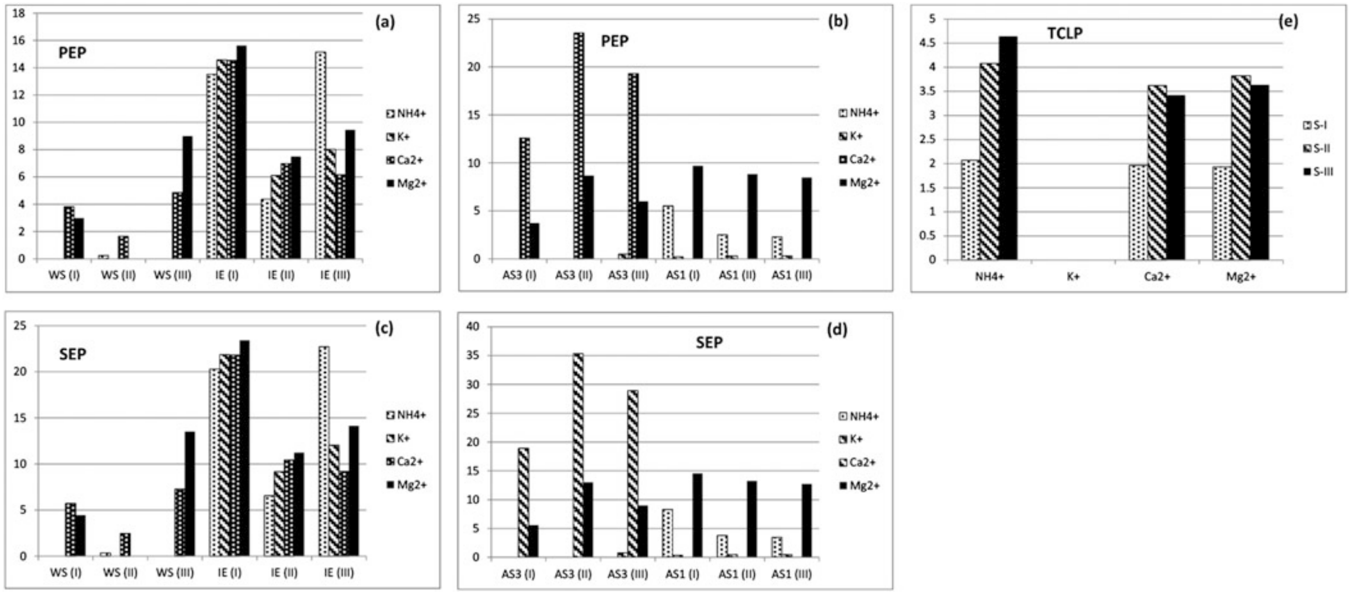


Fig. 9.8 Cation concentrations (mg/L) in different extractant solutions from parallel extraction (PEP) (**a**) and (**b**), sequential extraction (SEP) (**c**) and (**d**) and TCLP (**e**) by IC. *WS* water soluble, *IE* ion exchangeable, *AS (1 and 3)* acid soluble at pH 1 and 3; I, II and III represent three pond ash samples; and S represents sample

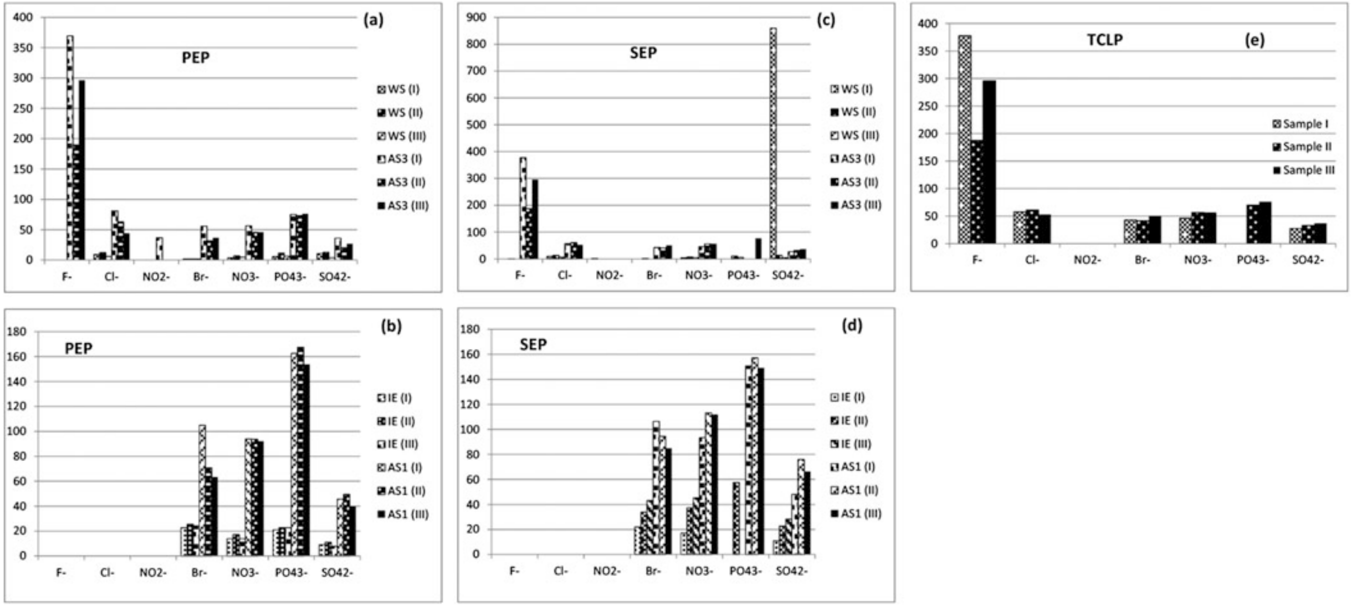


Fig. 9.9 Anion concentrations (mg/L) different extractant solutions from parallel extraction (PEP) (**a**) and (**b**), sequential extraction (SEP) (**c**) and (**d**) and TCLP (**e**) by IC; *WS* water soluble, *IE* ion exchangeable, *AS (1 and 3)* acid soluble at pH 1 and 3; I, II and III represent three pond ash samples; and S represents sample

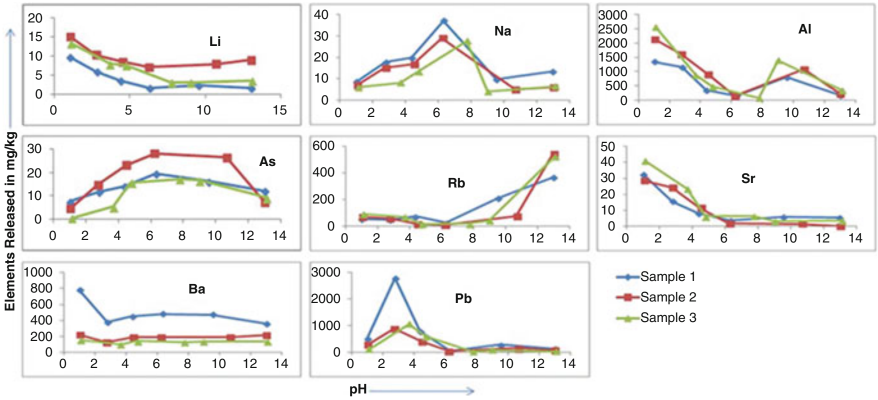


Fig. 9.10 Variation of leached concentration (mg/L) of selected alkali metals, alkaline earth metals, post-transition metals and metalloids with pH

considerably reduced in the low acidic and alkaline pH ranges. After pH value of 10, leaching of Sr from all the pond ash samples remained almost constant. Leaching of Ba was highest below a pH of 2 and was least in the pH range of 2 to 4. Al and Pb belong to the post-transition metals in the Periodic Table. Leaching behaviour of the two metals were significantly different from each other. Al leached in high concentrations in low pH and high pH conditions, whereas leaching of Pb was maximum in acidic pH conditions (pH 1 to 4). Al leaching was least in the pH range of 6–8 where its solubility is known to be at its minimum. Pb leached to a lesser extent in moderately acidic to alkaline pH range compared to low pH condition. Arsenic (As) is the only metalloid that was analysed by ICP-MS. Leaching of As was high in moderately acidic to moderately alkaline pH range. For all the pond ash samples, neither low pH nor high pH conditions were favourable for leaching of As. Considering the leached concentrations of all the elements shown in Fig. 9.10, leaching of Al, Ba, Pb and Rb were much higher compared to other elements. As, Ba and Pb are elements of potential health concern due to their toxicity.

Figure 9.11 shows leaching trends of some selected transition elements. Leaching trends of Ti, Sc, Co, Ni, Zn, Fe, Ag, Ta and Ir were almost similar in nature, i.e., maximum leaching of those elements occurred in low pH range compared to other pH ranges. V and Mo leached to the maximum extent in high pH range compared to other pH ranges. Cd leached high in pH range of 2–6. Cr and Cu leached in high concentrations both in acidic and alkaline pH conditions and least in moderately acidic to moderately alkaline pH conditions. Alkaline pH condition was unfavourable for high leaching of Ti, Co, Ni, Zn, Fe, Y, Ag, Cd and Ta. V and Sc leached in less concentration in moderately acidic to moderately alkaline pH range. Low pH conditions were unfavourable for leaching of Mo and highly favourable for Ir. Considering the leached concentrations of all the elements shown in Fig. 9.12, leaching of Ti and Mo were much higher compared to other

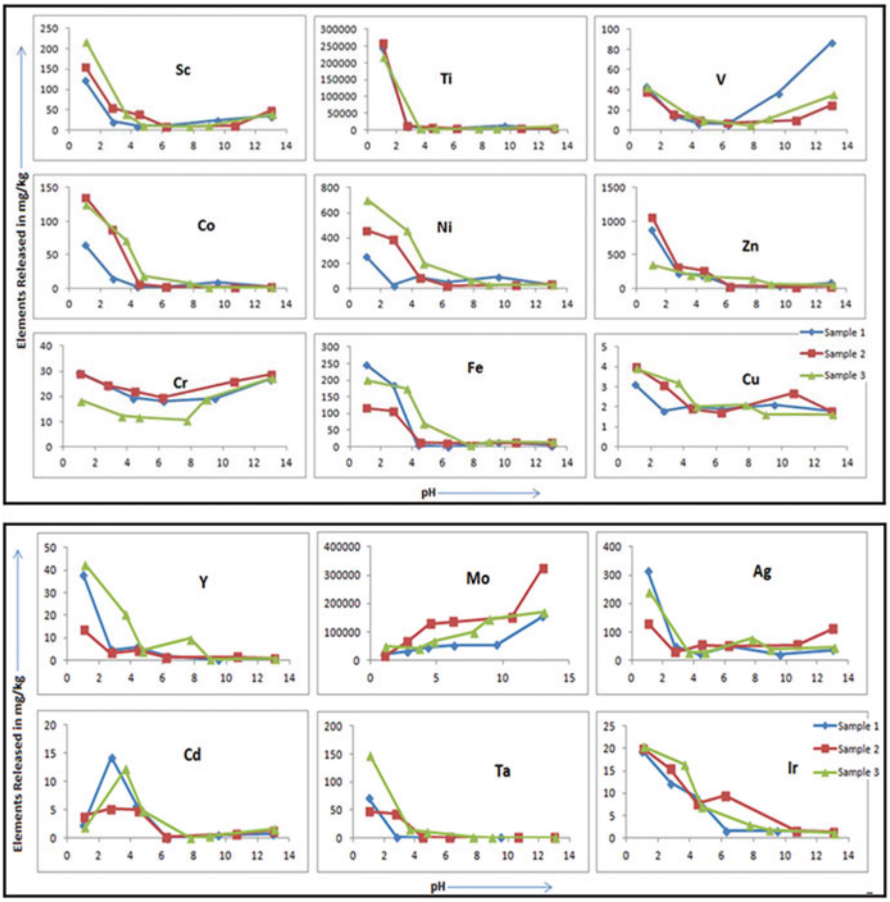


Fig. 9.11 Variation in leached concentrations (mg/L) of selected transition metals from pond ash as a function of pH

elements. Moderately high leaching was observed in case of Sc, V, Co, Ni, Zn, Fe, Ag and Ta varying from few to 1500 mg/kg of pond ash samples. Cr, Cu, Cd and Y leached in very less concentrations. Cd, Cr and Cu are elements of potential health concern among the elements shown in Fig. 9.11. Considering these three elements, it can be said that both extremely acidic and extremely alkaline pH conditions prevailing in ash ponds can result in significant leaching of Cr and Cu, whereas moderately acidic pH condition is suitable for leaching of Cd.

Figure 9.12 shows leaching trends of some selected lanthanides and actinides. La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu belong to the lanthanide series and Th and U belong to the actinides series. Leaching trends of all the lanthanides and actinides were almost similar i.e., leaching of these elements was high under low to moderate pH conditions. Alkaline pH conditions were observed to be unsuitable for leaching of all the elements. Leaching of La, Ce, Pr, Nd, Sm, Gd

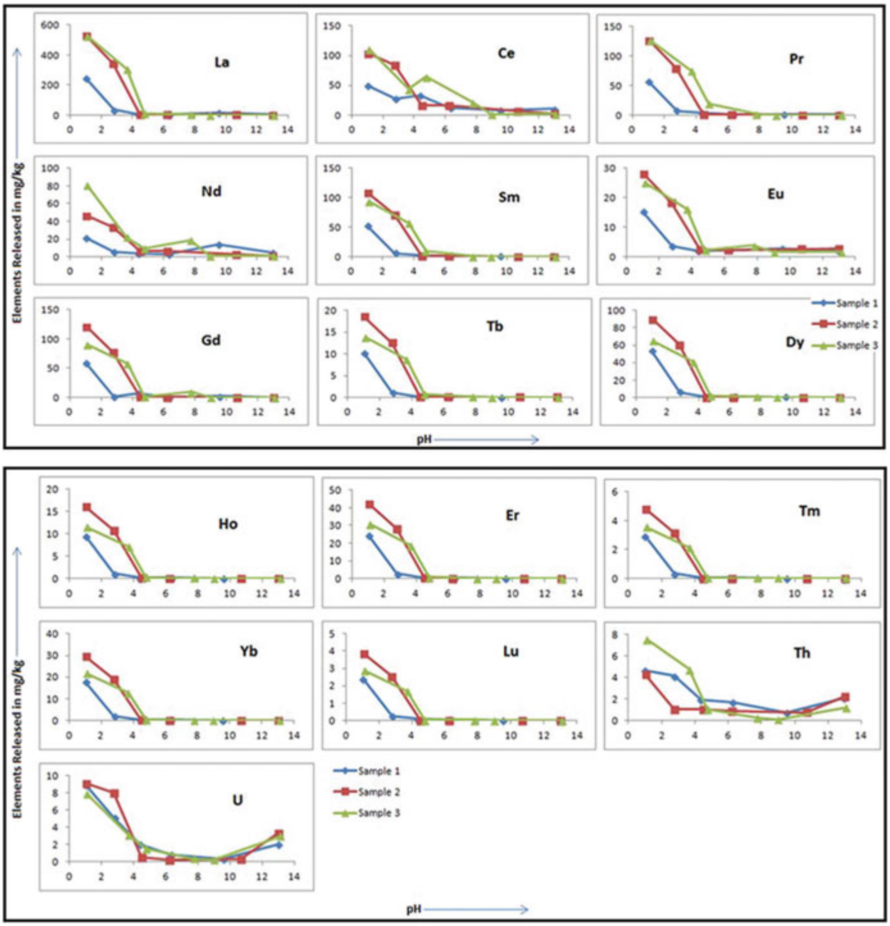


Fig. 9.12 Variation of leached concentrations (mg/L) of selected lanthanides and actinides from pond ash with pH

and Dy were much higher compared to other elements. Moderately high leaching (varying from few to 50 mg/kg of pond ash) was observed in case of Eu, Tb, Ho, Er and Yb. Tm, Lu, Th and U leached in very less concentrations (varying from less than 1–10 mg/kg of pond ash). Lanthanides and actinides are responsible for several human health hazards. Lanthanides are toxic to human health to some extent; some of them are explosive in powder form. Actinides such as Th and U are radioactive and carcinogenic. So these elements are of potential concerns considering their environmental impacts. In actual ash pond environment, low to moderately high pH conditions can be potent for leaching of these elements.

3.4.1 IC Analyses Results of Liquid Samples

IC analyses for determining cation and anion concentrations in all liquid samples were performed (results are not shown). NH_4^+ and Ca^{2+} ions mostly leached in the 4 to 8 pH range and Mg^{2+} mostly leached in the low pH range (less than 4). Both for NH_4^+ and Ca^{2+} ions, low pH and high pH conditions were unfavourable for leaching. In case of Mg^{2+}, decrease in pH increased leaching. Results of K^+ analysis were not reported due to interference by K^+ ions present in KOH solution used for controlling pH.

Leaching trends of F^- and SO_4^{2-} varied from sample to sample. Cl^- and NO_2^- are highly soluble regardless of pH conditions. Alkaline pH condition slightly increased leaching of NO_2^-. Increase in pH increased leaching in case of Br^-. PO_4^{3-} leached slightly higher in high acidic pH condition. Results of NO_3^- analysis were not given due to interference by NO_3^- ions present in HNO_3 solution used for controlling pH.

3.5 Time Dependent Leaching Behaviour of Pond Ash

Results of the time dependent studies show leaching behaviour of alkali metals, alkaline earth metals, post-transition metals and metalloids. Li, Na and Rb belong to the alkali metals group in the Periodic Table. Leaching trends of each element was considerably different from the other elements and all three pond ash samples did not give the same leaching results for each metal. For simplicity, the leaching behaviour of all elements is divided into four categories:

(i) Elements whose leached concentrations increased over time included Li, Al, Sr, Pb, Rb, Co, Ni, Cr, Cd, Ir, Th, U, La, Dy, Ho, Er, Tm, Yb and Lu. The increase in leached concentrations over the 7-day period shows that the release of these elements from the solid samples is a relatively slow process.
(ii) Elements whose leached concentrations decreased over time included Na, As and Gd, demonstrating the high solubility and fast reaction kinetics of these elements.
(iii) Elements whose leached concentrations were constant over time included Ba only.
(iv) Elements whose leached concentrations showed variable behaviour in the three different samples tested included: Sc, Fe, Cu, Y, Mo, Ag, Ta, Tb, Ce, Pr, Nd, Sm and Eu.

3.5.1 IC Analyses Results

Results of IC analyses of the cations present in the liquid or supernatant samples in the above tests can be categorized similarly:

(i) Ions whose leached concentrations increased over time included only magnesium,

(ii) Ions whose leached concentrations were constant over time included sulphate, chloride and phosphate. These ions are considered to be highly soluble and unlikely to precipitate out of solution.

(iii) Ions whose leached concentrations showed variable behaviour over time in the three samples tested included fluoride, bromide, nitrite and nitrate.

No ion concentrations were found to decrease in the time dependent studies demonstrating the increasing solubilization of ions and lack of precipitation of these ions over time.

3.6 Column Leaching Test

Leaching behaviours of some selected alkali metals, alkaline earth metals, post-transition metals and metalloids were evaluated. All the metals in this group showed first flush leaching pattern. It means there was high initial leaching of those metals followed by a decrease in it over time. In case of Al, leached concentration increased on the second day of experiment and then attenuated over time. Moderate initial leaching (leached concentrations varying from 5 to 160 mg/kg) was observed in case of Al, Na, As, Pb and Ba. Other metals leached within 0 to 10 mg/kg concentration range.

All the elements showed first flush leaching pattern. In case of Ti, leaching increased up to 3rd day while leaching of Co and Ta increased up to 2nd day and then attenuated. In case of Y, similar leaching pattern was observed on the first two days of experiment and then its leaching attenuated. High leaching was observed in case of Ti and Mo varying from 10 to 60,000 mg/kg. Moderate leaching was observed in case of Zn, Ni, Cr, Fe and Ta, varying from 0 to 90 mg/kg. Other elements were traced in low concentrations varying from 0 to 10 mg/kg. Leaching trends of some selected lanthanides and actinides showed that leaching of these elements increased up to 3rd day of experiment and then attenuated. Low leaching was observed in case of all the elements.

3.6.1 IC Analyses

IC analyses were performed on all the filtered leachate samples obtained from Column Leach Test. In case of cation analyses, only NH_4^+ and Ca^{2+} could be detected by the instrument. NH_4^+ ion concentration gradually decreased over time both for samples obtained using rain water and reagent grade water (Ultrapure water – UW) as leaching solutions. Ca^{2+} ion concentration initially increased (on the second day of experiment) and then gradually decreased over time. So first flush leaching behaviour of these two cations was observed.

Anions Cl^-, PO_4^{3-} and SO_4^{2-} showed first flush leaching behaviour. Other two anions namely, F^- and $NO^-{}_3$ did not strictly follow first flush leaching behaviour. Release of these two anions increased up to 4th day in case of F^- and up to 3rd day in case of $NO^-{}_3$. Concentrations of all the ions analysed were much less than that found in case of pH and time dependent leaching studies. Concentrations of all anions and K^+ cation were found in all the samples in much less concentrations compared to WHO drinking water guidelines for these ions.

Comparing the results of pH and time dependent studies with column leach study, it can be concluded that there is significant adsorption of the elements (present in the pond ash samples) by the soil layer used in column leach test. Rain water enhanced leaching of almost all the elements (compared to that leached in contact with reagent grade water). First flush concentrations of toxic elements such as As, Ba, Pb, Cd, Cr, Cu and radioactive elements such as Th and U in the effluent leachates are higher than the WHO prescribed limits for drinking water. So there remain chances of contamination of groundwater within a short period of time after occurrence of rainfall on the ash ponds due to transport of these elements through ash and soil layers.

Variation in pH was monitored in all studies described here. pH of all column leachate samples was initially close to 7 and increased over time to pH of 8 to 9, i.e., it can be concluded that the samples turned more alkaline over time. But in case of time dependent leaching behaviour experiment (done only on the pond ash samples) pH of the samples turned more acidic over time. So the soil layer in case of column leach test played an important role in changing pH of the leachates and changing the leaching behaviour of different elements (present in pond ash) into the leachates.

Since the experiment was done at lab-scale, the results may vary from that done in field scale. In the field, several parameters like thickness of pond ash and soil layers, percolation rate of rain water through the ash, etc. are likely to be different and may affect leaching pattern of the elements. So all the conclusions made regarding potential for groundwater contamination may not be pertinent under actual field conditions. Al, Mo and Ba were found in the groundwater samples at the study area exceeding WHO (except Ba) and IS 10500-2012 recommended limits, other elements being within the limits. Results of column leach test also indicate high first flush concentrations of these elements. Regarding other elements, it is possible that they are adsorbed in the soil layers of the study area and may not percolate to groundwater.

4 Conclusions

The following conclusions can be drawn from the present study:

(i) Leached concentrations of different elements present in pond ash samples varied with pH of the leaching solutions during parallel extraction procedure

(PEP). Leaching of toxic elements like Cr, Zn, Pb, Cd and Cu increased with decrease in pH of the leaching solutions. Toxic heavy metals and radioactive elements in the water soluble fraction were found in concentrations exceeding their WHO prescribed limits for drinking water. XRD analyses results showed changes in mineralogical compositions of the pond ash samples after parallel extraction. This may have occurred due to leaching of mineral (s) during parallel extraction.

(ii) Enhanced leaching potentials of toxic metals such as Cr, Zn, Pb, Cd and Cu were observed with decrease in pH during sequential extraction. Results of leached concentrations obtained from parallel and sequential extraction of pond ash samples are in agreement even though the nature of the tests is very different.

(iii) From the results of TCLP conducted on three pond ash samples, it can be concluded that leachates from the pond ash samples are environmentally hazardous in nature.

(iv) Wet disposal of pond ash may cause leaching of several toxic and radioactive elements into the environment (soil and groundwater) and was affirmed by the results of parallel and sequential extractions. Acidic nature of the pond ash samples may enhance leaching of those elements. So, wet disposal of pond ash has serious environmental concerns.

(v) It can be concluded from IC analyses results of the liquid samples obtained after PEP and SEP that almost all the cations and anions leached mostly in ion exchangeable fraction. IC analyses of leachate samples obtained from TCLP showed high concentration of F^-. Other anions leached in moderate amounts. All the cations (except K^+ which was absent) leached in low amounts.

(vi) Results of pH dependent leaching behaviour of pond ash samples showed that in actual ash pond environment, low to moderately high pH conditions can be potent for leaching of both toxic and radioactive elements.

(vii) Results of time dependent leaching behaviour of pond ash samples showed that pH of the samples turned more acidic with time. Leaching of toxic elements such as Cr, Cu, Zn, Pb and Cd and radioactive elements such as Th and U increased with time. Same conclusions were drawn regarding pH dependent leaching behaviour of pond ash samples.

(viii) IC analyses of cations present in time dependent test samples showed leaching of NH_4^+ decreased over time and leaching of Ca^{2+} initially increased and then again decreased. Leaching of Mg^{2+} increased over time. pH dependent test results showed high leaching of Ca^{2+} and NH_4^+ in 4 to 8 pH range and decrease in pH increased leaching of Mg^{2+}. pH of the samples became more acidic over time in case of time dependent test. IC analyses of anions present in time dependent test samples showed leaching trends of F^-, NO_2^-, Br^- and NO_3^- were different for different samples. Leaching trends of other anions like Na^+, Cl^- and PO_4^{3-} did not change significantly over time. Only Cl^- showed similar leaching trend that was observed in pH dependent test.

(ix) pH of the solutions obtained from column leach test turned alkaline over time which is in contrast with the observations from time dependent leaching test. First flush concentrations of toxic elements such as As, Ba, Pb, Cd, Cr and Cu and radioactive elements such as Th and U in the effluent leachates were higher than the WHO prescribed limits for drinking water. Again comparing column leach test data with pH and time dependent studies it is clear that significant adsorption of the elements (present in the pond ash samples) took place in the soil layer used in column leach test. So the soil layer in case of column leach test played an important role in changing pH of the leachates thus changing the leached concentrations of the elements.

References

Chang, C.Y., Wang, C.F., Mui, D.T. and Chiang, H.L., 2009. Application of methods (sequential extraction procedures and high-pressure digestion method) to fly ash particles to determine the element constituents: A case study for BCR 176. *Journal of Hazardous Materials*, **163(2–3)**, 578–587.

Ghosh, A. and Subbarao, C., 1998. Hydraulic conductivity and leachate characteristics of stabilized fly ash. *Journal of Environmental Engineering ASCE*, **124(9)**, 812–820.

Huang, S., Chang, C.Y., Trong, D., Chang, F.C., Lee, M.Y. and Wang, C.F., 2007. Sequential extraction for evaluating the leaching behavior of selected elements in municipal solid waste incineration fly ash. *Journal of Hazardous Materials*, **149(1)**, 180–188.

Indian Meteorological Department (IMD), 2015. Downloaded from http://www.imd.gov.in/

Iyer, R., 2002. The surface chemistry of leaching coal fly ash. *Journal of Hazardous Materials*, **B93(3)**, 321–329.

Konstantinou, I.K. and Albanis, T.A., 2000. Adsorption-desorption studies of selected herbicides in soil-fly ash mixtures. *Journal of Agricultural and Food Chemistry*, **48(10)**, 4780–4790.

Mandal, A. and Sengupta, D., 2005. Radionuclide and trace element contamination around Kolaghat Thermal Power Station, West Bengal – Environmental implications. *Current Science*, **88(4)**, 617–624.

Shivpuri, K.K., Lokeshappa, B., Kulkarni, D.A. and Dikshit, A.K., 2011. Metal Leaching Potential in Coal Fly Ash. *American Journal of Environmental Engineering*, **1(1)**, 21–27.

Tessier, A., Campbell, P.G.C. and Bisson, M., 1979. Sequential extraction procedure for the speciation of particulate trace metals. *Analytical Chemistry*, **51(7)**, 844–851.

USEPA SW 864 method 1311, 2011 Toxicity characteristic leaching procedure.

Chapter 10
WQI, DRASTIC and Contaminant Transport Modelling Using WiscLEACH 2.0

Prasenjit Ghosh and Sudha Goel

1 Introduction

In the present chapter, impacts of flyash generation on local river water, ground water and river sediments are discussed. Rupnarayan river water and groundwater samples were collected from the study area and analysed for trace elements and different ions. The concentrations of different elements and ions (both in river and groundwater) were then compared with their recommended acceptable limits prescribed by WHO, IS 10500-2012 and IS 2296-1982 to assess their suitability for drinking and domestic uses respectively. Water Quality Index (WQI) and DRASTIC were applied for qualitative analyses of river water and ground water, respectively. Soil samples were collected from the surrounding areas of the ash ponds in Kolaghat and one soil sample was collected from the campus of IIT Kharagpur as the background or uncontaminated soil sample. Mineralogical compositions and trace metals concentrations in the soil and sediment samples were determined and compared with that of background soil to assess the level of land and river bed contamination. Pond ash and fly ash are used as filling materials in local roads. Since pond ash contains heavy and toxic metals, it is likely that these metals will leach from pond ash when in contact with rain water. Contaminant transport modelling of two metals, Ba and Cr from pond ash stabilized base layers of roads into the soil vadose zone and groundwater zone was done using WiscLEACH 2.0

P. Ghosh (✉)
Centre for Environmental Science and Engineering, Indian Institute of Technology Bombay,
Powai, Mumbai 400076, India
e-mail: ami.prasenjit@gmail.com

S. Goel
Civil Engineering Department, Indian Institute of Technology Kharagpur,
Kharagpur 721302, WB, India

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_10

software. The maximum concentrations of these metals and their corresponding locations in the two zones after 1, 10 and 50 years of their first leaching were predicted using this model.

2 Materials and Methods

2.1 *Water and Sediment Sample Collection*

Three water samples were collected from the river Rupnarayan in Kolaghat in the East Midnapore district of West Bengal on 2nd October, 2013. A boat was taken from one bank to the other for water sample collection; the approximate path of the boat is shown in Fig. 10.1. Samples were collected first, from one bank of the river, then from midstream of the river and the 3rd and last sample was collected from the opposite river bank. River water samples were named as per the sequence of their collection as shown in Fig. 10.1 One river sediment sample was also collected from the bed of the river.

Two groundwater samples were collected on the same day from two villages situated near two banks of the river. Approximate locations of groundwater sample collection sites are shown in Fig. 10.1. They were named as groundwater samples 1 and 2 accordingly.

All the water samples were collected in plastic buckets and used for experiments after filtering through 0.45 μ Nucleopore filter papers.

2.2 *Soil Sample Collection*

One background soil sample was collected from the ground around the Civil Engineering Department in IIT Kharagpur on 27th February, 2014. It was collected in a plastic bucket and was immediately sealed with plastic cover to prevent exposure to sunlight. Total 12 numbers of soil samples were collected from areas neighbouring the three ash ponds on 11th March, 2014 (shown in Chap. 8, Fig. 10.3). From each site, four numbers of soil samples were collected from depths of 0 cm (top soil), 25 cm, 50 cm and 75 cm below ground level by boring. One 1.25 m long stainless steel hand soil auger was used for boring and sample collection. Samples sticking to the auger were rejected and samples from the inner side of the auger were collected in polyethylene packets. Soil sample 1 was collected from the area surrounding the ash pond from where pond ash sample 1 was collected. Accordingly, other soil samples were named as soil samples 2 and 3.

Fig. 10.1 Collection path of river water from Rupnarayan river and groundwater sample collection sites

2.3 *Analyses of Water, Soil and Sediment Samples*

2.3.1 Water Sample Analyses

All five liquid samples (two groundwater and three river water samples) were taken for trace metals analyses by 820 ICP-MS instrument. Regarding preparation of the liquid samples for metal analyses, 40 ml of each of the samples were taken in 100 ml PMP beakers and the same were acidified to 2% by adding 70% concentrated HNO_3. Then 8 ml of each of the acidified samples were taken for trace metals analyses. FS-AAS analyses were done to measure concentrations of Cu and Fe. IC analyses were also done to estimate different cations and anions concentrations in the samples. Same standards (as used in case of parallel extraction) were used for calibration of the instruments.

2.3.2 Assessment of Soil Contamination Due to Dumping of Pond Ash

Soil samples were tested by a panalytical high resolution XRD-I PW 3040/60 diffractometer following the same procedure as for the pond ash samples. At first, the soil samples were dried in a hot air oven at 105 °C for 24 h. Then they were homogenized using a mortar and a pestle. Grinding was done carefully to ensure that there was no granular fraction left. Sieving was not done because doing so may exclude some important mineral(s) that may not be present in the finer fraction obtained after sieving. The powder obtained after grinding was used for XRD analyses.

Analyses of trace elements in the soil samples (in pellet form) were conducted using LSX-213 Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA ICP-MS) coupled with an Agilent 820 ICP-MS Quadrupole. Fresh pellets (20 mm diameter and 6 mm thick) of the soil samples were prepared using a hydraulic press by applying a pressure of 5 ton. The pellets were then stored in plastic petri dishes until they were analysed by LA ICP-MS. NIST-612 (National Institute of Standards and Technology) was run as standard and NIST-610 was run as unknown during the analyses.

2.3.3 Assessment of Sediment Contamination

Panalytical high resolution XRD-I PW 3040/60 diffractometer was used for determining mineralogical compositions of sediment sample. Same procedure as was done in case of soil samples was followed for performing the experiment.

Trace elements analyses were also performed by LA ICP-MS following the same procedure discussed in case of soil samples. Same standard and unknown was used during the experiment.

2.4 WQI and DRASTIC Approaches

2.4.1 Water Quality Index (WQI) for Assessing River Water Quality

Water Quality Index (WQI) is a dimensionless single number which is obtained after combining multiple water quality factors by normalising the values of those factors to respective rating curves. WQI developed by the U.S. National Sanitation Foundation (NSF) in 1970 was followed to assess the current water quality of the river Rupnarayan. Nine water quality parameters namely Dissolved Oxygen (DO), Fecal Coliform (FC), pH, BOD_5, NO_3^-, PO_4^{3-}, Temperature deviation (ΔT), Turbidity and Total Solids (TS) of the Rupnarayan river water were measured following the methods listed in Table 10.1.

Measured values of the parameters were then used to find the corresponding sub-index values (S_i) from the standard graphs of those parameters. The sub-index values were then multiplied by their respective weighting factors and added up to obtain the WQI value representing the overall river water quality. The water quality rating values listed in Table 10.2 were used to rate the overall river water quality.

Table 10.1 Details of WQI parameters and their measurement

Parameters measured	Method instrument used for measurement	Weighting factor (Wi)
DO (% Saturation)	DO measuring probe	0.17
FC	Membrane filtration method	0.15
pH	pH measuring electrode	0.12
BOD_5	Standard 5 days BOD test	0.1
NO_3^-	Metrohm 761 Compact IC	0.1
PO_4^{3-}	Metrohm 761 Compact IC	0.1
ΔT	Thermometer	0.1
Turbidity	Digital Nephelometric Turbidimeter	0.08
TS	Standard methods	0.08

Table 10.2 Chart for rating river water quality

WQI value	Water quality rating
91–100	Excellent
71–90	Good
51–70	Medium
26–50	Bad
0–25	Very bad

Source: Canter (1996)

2.4.2 "DRASTIC" Index for Assessing Groundwater Pollution Vulnerability

Groundwater is the main source of drinking water in East Midnapur district and is vulnerable to pollution. Assessing the vulnerability of groundwater to pollution is an important step because adverse health impacts are associated with the same. "DRASTIC" is an aquifer-vulnerability-mapping technique developed for assessing groundwater pollution potential which is based on the hydro-geological setting of the study area. Vulnerability is defined based on the intrinsic characteristics of groundwater as well as the study area. DRASTIC was developed by the U.S. Environmental Protection Agency, and is one of the most widely used methods for identifying areas susceptible to groundwater contamination. Geographic Information System (GIS) is generally followed to develop pollution susceptibility maps of an area under study. The "DRASTIC" method uses a set of seven hydrogeologic parameters to classify the pollution potential of an aquifer situated at the study area. These parameters are:

1. Depth to groundwater table (D),
2. Recharge rate of aquifer (R),
3. Aquifer media (A),
4. Soil media (S),
5. Topography (T),
6. Impact of the vadose zone (I) and
7. Hydraulic conductivity of aquifer (C).

For a given area under study each parameter is rated on a scale of 1–10, which indicates the relative pollution potential of the given parameter in that area. Weight values from 1 to 5 are assigned to the parameters which express their relative importance with respect to each other. DRASTIC tables can be listed either using weights for factors having general applicability or for factors related to potential pollution from pesticide applications. After rating all the parameters, each rating is multiplied by the assigned weight to them and summed up to get the Drastic Index (DI) which is used for assessing the vulnerability of ground water of that particular area to pollution. The equation for calculating the *DI* is:

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \tag{10.1}$$

where w = weight and r = rating.

A site having a higher DI value represents greater potential for groundwater pollution.

2.5 Contaminant Transport Modelling Using WiscLEACH 2.0 Software

It is important to understand how chemical or biological contaminants are transported through subsurface aquifer systems. The Advection-Dispersion-Reaction Equation (ADRE) is a partial differential equation that is used to model changes in the concentration of a chemical species in an advection-dispersion-reaction process. In this process, a chemical species undergoes a reaction, can disperse in the solvent and is transported by the bulk movement of the solvent (advection). Advection is a transport mechanism of a substance by a fluid due to the fluid's bulk motion. The entire process depends on flow of the bulk fluid and cannot take place in rigid solids. A chemical reaction is a process that leads to the transformation of one set of chemical substances to another. Dispersion is a state of a mixture in which fine particles of one substance are scattered or dispersed throughout another substance, generally the bulk fluid.

Transport of two contaminants namely Ba and Cr was simulated using the online version of WiscLEACH 2.0 software. It is a computing tool used for simulating water and solute movement in two-dimensional variably saturated and unsaturated media. Three analytical solutions to the advection-dispersion-reaction equation are combined in WiscLEACH to develop a method for assessing impacts on groundwater and the soil vadose zone by leaching of trace elements from fly ashes used in stabilization of roadways (Cetin et al. 2012). 2D–Water Leach Test Model was used for all the simulations in the present study. WiscLEACH simulations were conducted to study the locations of maximum soil vadose zone and groundwater concentrations of Ba and Cr leaching from pond ash stabilized base layer of a typical roadway. Reason for choosing Ba and Cr for the simulation studies was to check whether their concentrations in ground water after certain time period exceeds WHO and IS: 10500–2012 recommended limits for drinking water. Contours of these trace metals (Ba and Cr) concentrations were predicted after three different years (1, 10 and 50 years after the elements first leached) at the centreline of the pavement and at the vicinity of point of compliance. Different parameters related to ground water, vadose zone and roadway layers were taken into consideration for performing the simulations.

Input to the model consisted of the annual precipitation rate which was taken from data available at the official website of Indian Meteorological Department for the district East Midnapur in West Bengal, India. Point of compliance (POC) was assumed to be 20 m from the centre of the roadway. This POC was chosen as the target location because the concentrations of metals at POC are less sensitive to the pavement width and shoulder width (Leij et al. 2000). Physical properties of the pavement layers were assumed from data available (for a typical highway) in IRC-37, 2012 code. Physical properties of background soil (subgrade) were tested in laboratory. Leached concentrations of the trace metals Ba and Cr were taken from the results of Batch Water Leach Test (WLT) using Pond Ash-Soil-Lime mixtures. Batch Water Leach Test (WLT) procedure is discussed in this section later. The depth of groundwater and hydraulic gradient values of the study area were taken from data available in the website of Central Ground Water Board and Ground Water Information System for the district East Midnapur. Different transport parameters of the subsurface layers and the contaminants consisted of retardation factors of the contaminants in subgrade and stabilized layers, molecular diffusion coefficients of the contaminants, horizontal and vertical dispersivities above and within groundwater, etc.

Retardation factor of a contaminant for a particular solid sample is a function of organic carbon fraction, bulk density and porosity of the sample and octanol-water partition coefficient of the contaminant. Loss on ignition (LOI) values of pond ash-soil-lime mixtures (used in batch water leach test) were determined in the laboratory by igniting them (after oven drying) between 350 and 440 °C in muffle furnace and measuring the % weight loss after ignition. Organic carbon fractions of the samples were then calculated by dividing LOI values by 1.72. Bulk densities of the samples were measured in the laboratory following the same procedure adopted for pond ash samples. Porosities of the samples were also measured at the same time. Octanol-water partition coefficients of all the samples were assumed to be 190 L/kg for both Ba and Cr.[1]

Retardation factor for subgrade was assumed to be 3.5 for all simulations (Aydilek and Cetin 2013). Molecular diffusion coefficients of both Ba and Cr were assumed to be 0.032 m/year (Pang et al. 2002). Horizontal dispersivity above groundwater was assumed to be 0.192 m for silty clay vadose zone (Perfect et al. 2002). Vertical dispersivity above groundwater was assumed to be approximately 10% of horizontal dispersivity (Aydilek and Cetin 2013). Horizontal and

---

[1] www.epa.gov/athens/publications/reports/Ambrose600R05074PartitionCoefficients.pdf

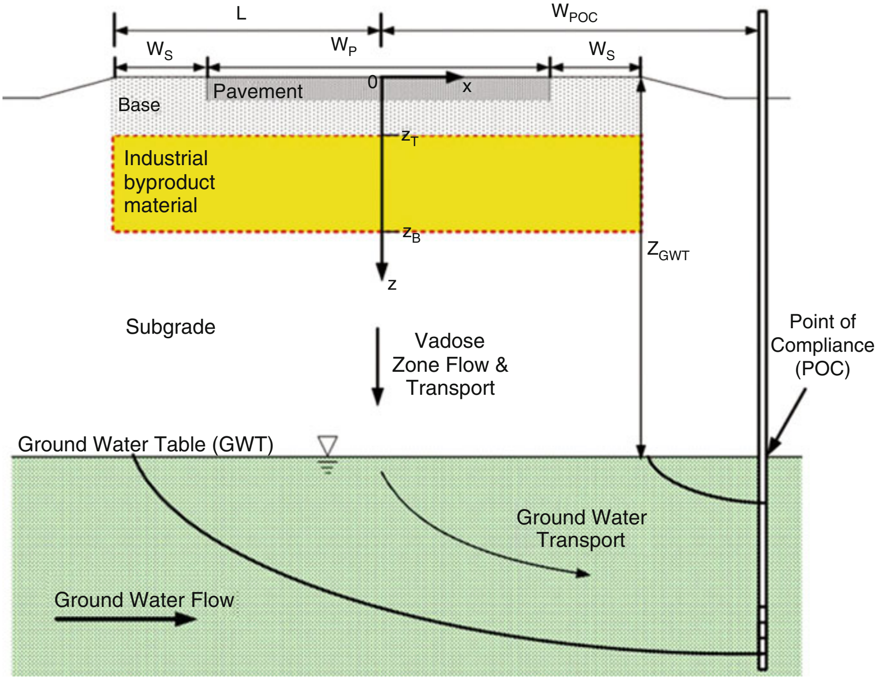


Fig. 10.2 Conceptual model of WiscLEACH for application in roadway stabilization

vertical dispersivity values within groundwater were assumed to be 5 m and 0.1 m respectively (Woumeni and Vauclin 2006).

Figure 10.2 shows a schematic diagram of a typical highway structure including different layers, shoulders, vadose zone and groundwater zone.

Different parameters shown in the conceptual model are explained below:

$W_S =$ Shoulder width (m),
$W_P =$ Pavement width (m),
$W_{POC} =$ Point of compliance (m),
$L =$ Length of shoulder and half of pavement width (m),
$X =$ Horizontal distance from centre of pavement (m),
$Z =$ Vertical (downward) distance from centre of pavement (m),
$Z_T =$ Depth to top of stabilized layer (m),
$Z_B =$ Depth to bottom of stabilized layer (m), and
$Z_{GWT} =$ Depth to groundwater (m).

Different assumptions made for the simulation study as per Aydilek and Cetin (2013) are listed below:

(i) All materials in the profile are assumed to be homogeneous and isotropic.
(ii) All precipitation falling on the pavement surface, shoulders and surrounding grounds will infiltrate through the soil.

(iii) Only steady 1-D vertical flow takes place in the pavement layers and the soil vadose zone and the flow rate q_{v} is determined by comparing with the least conductive layer in the profile and the annual precipitation rate.

(iv) There is no loss of water and the water infiltrates to the soil vadose zone towards ground water without any loss on the pavement and ground surface.

(v) Surface runoff and evaporation from the pavement surface are ignored.

(vi) A first-flush leaching from the stabilized base layer is assumed to follow the ADRE with linear, instantaneous and reversible sorption.

(vii) The transport of trace elements that leach into ground water takes place in both, horizontal and vertical directions, although horizontal movement is dominant in ground water.

(viii) The transport of trace elements in ground water is assumed to follow the ADRE with instantaneous, reversible and linear sorption.

(ix) No chemical or biological reactions were considered in these simulations.

2.5.1 Model Formulation in Vadose Zone

Transport in the vadose zone beneath the stabilized base layer is assumed to follow the ADRE for 1-D steady state with 2-D dispersion and linear, instantaneous and reversible sorption. Equation (10.2) (Leij et al. 2000) is used in WiscLEACH to provide an analytical solution that can be used for the lagged response leaching pattern of a contaminant in the vadose zone.

$$R\frac{\partial C}{\partial t} = D_x\frac{\partial^2 C}{\partial x^2} + D_z\frac{\partial^2 C}{\partial z^2} - \vartheta_z\frac{\partial C}{\partial z} \tag{10.2}$$

Equation (10.2) can be represented by the mass balance diagram shown in Fig. 10.3.

Different terms related to the above equation are listed below:

$C =$ Metal concentration (mg/l),
$T =$ Time (year),
$X =$ Horizontal distance from the centreline of the pavement (m),
$Z =$ Depth below ground surface (m),
$\vartheta_{\mathrm{z}} =$ Seepage velocity or pore water flow velocity in vertical direction (m/year),
$D_{\mathrm{x}} =$ Dispersion coefficient in x-direction (horizontal) (m^2/year),ν
$D_{\mathrm{z}} =$ Dispersion coefficient in z-direction (vertical) (m^2/year) and
$R =$ Retardation factor, unitless.

The term $\vartheta_z\frac{\partial C}{\partial z}$ represents advective transport while $D_x\frac{\partial^2 C}{\partial x^2}$ and $D_z\frac{\partial^2 C}{\partial z^2}$ represent dispersive transport.

The analytical solution to Eq. (10.2) is obtained by applying the following initial and boundary conditions (Leij et al. 2000):

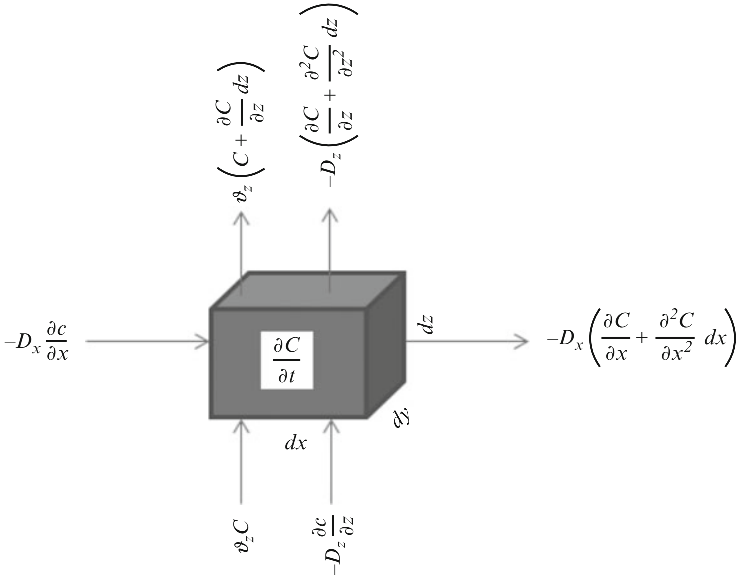


Fig. 10.3 Mass balance diagram for transport of contaminants in vadose zone

$$C(x,z,t=0)=\begin{cases} C_0, \text{at}\, z_T < z < z_B \,\text{and} -L < x < L \\ 0, \text{otherwise} \end{cases} \tag{10.3a}$$

$$\left[\upsilon_z C - D_z\frac{\partial C}{\partial z}\right]_{z=0} = 0 \tag{10.3b}$$

$$\frac{\partial C}{\partial x}(\pm\infty, z, t) = 0 \tag{10.3c}$$

$$\frac{\partial C}{\partial z}(x, \infty, t) = 0 \tag{10.3d}$$

where C_0 = Initial metal concentration (mg/l), z_T = Depth of the top of the fly ash stabilized base layer (m), z_B = Depth of the bottom of the fly ash stabilized base layer (m) and L = Sum of the width of the shoulder and half of the pavement width (m).

Equations (10.3a) and (10.3b) indicate that the fly ash stabilized base layer is the only source of trace elements and no trace elements are leached from the pavement and ground surface that are above the fly ash stabilized base layer. Eqs. (10.3c) and (10.3d) imply that the effect of dispersion and diffusion in the soil vadose zone is insignificant with distance from the centreline of the pavement structure and the pavement surface respectively. The analytical solution to Eqs. (10.2) and (10.3) is (Aydilek and Cetin 2013):

$$\begin{aligned} C(x,z,t) = \frac{C_0}{4}\Bigg\{ & e^{\left(\frac{\upsilon_z z}{D_z}\right)}\left[\left(\frac{1+\upsilon_z z}{D_z}\left(z+z_T+\frac{\upsilon_z t}{R}\right)\right)\operatorname{erfc}\left(\frac{R(z+z_T)+\upsilon_z t}{\sqrt{4RD_z t}}\right)\right] \\ & -\exp\left(\frac{\upsilon_z z}{D_z}\right)\times\left[\left(1+\frac{\upsilon z}{D_z}\left(z+z_B+\frac{\upsilon_z t}{R}\right)\right)\operatorname{erfc}\left(\frac{R(z+z_B)+\upsilon_z t}{\sqrt{4RD_z t}}\right)\right] \\ & +\operatorname{erfc}\left(\frac{R(z-z_B)-\upsilon_z t}{\sqrt{4RD_z t}}\right)-\operatorname{erfc}\left(\frac{R(z-z_T)-\upsilon_z t}{\sqrt{4RD_z t}}\right)+\sqrt{\frac{4\upsilon_z^2 t}{\pi R D_z}}\exp\left(\frac{\upsilon_z z}{D_z}\right) \\ & \left[\exp\left(-\frac{[R(z-z_B)+\upsilon_z t]^2}{4RD_z t}\right)-\exp\left(-\frac{[R(z+z_T)+\upsilon_z t]^2}{4RD_z t}\right)\right]\Bigg]\Bigg\} \\ & \times\left[\operatorname{erfc}\left(\frac{x-L}{\sqrt{\frac{4D_x t}{R}}}\right)-\operatorname{erfc}\left(\frac{x+L}{\sqrt{\frac{4D_x t}{R}}}\right)\right] \end{aligned} \tag{10.4}$$

Equation (10.4) is applicable for simulation of contaminant transport from the surface of the pavement to the groundwater table.

2.5.2 Model Formulation in Groundwater Zone

Equation (10.5) (Leij et al. 2000) is used in WiscLEACH to provide an analytical solution that can be used for the lagged response leaching pattern of a contaminant in groundwater zone.

$$R_w\frac{\partial C}{\partial t}=D_{xw}\frac{\partial^2 C}{\partial x^2}-\upsilon_h\frac{\partial c}{\partial x}+D_{zw}\frac{\partial^2 c}{\partial z^2}-\upsilon_z\frac{\partial C}{\partial z} \tag{10.5}$$

Equation (10.5) can be represented by the mass balance diagram shown in Fig. 10.4.

Different terms related to the above equation are listed below:

$C =$ Metal concentration (mg/l),
$T =$ Time (year),
$\vartheta_{\mathrm{h}} =$ Groundwater seepage velocity in horizontal direction (m/year),
$D_{xw} =$ Hydrodynamic dispersion coefficient in horizontal direction (m^2/year),
$\vartheta_z =$ Groundwater seepage velocity in vertical direction (m/year),
$R_w =$ Retardation factor in groundwater, and
$D_{zw} =$ Hydrodynamic dispersion coefficient in vertical direction (m^2/year).

In Eq. (10.5), the cross-dispersion terms are ignored due to the dominant horizontal flow in a uniform and isotropic medium. The analytical solution to Eq. (10.5) is obtained by applying the following initial and boundary conditions (Leij et al. 2000):

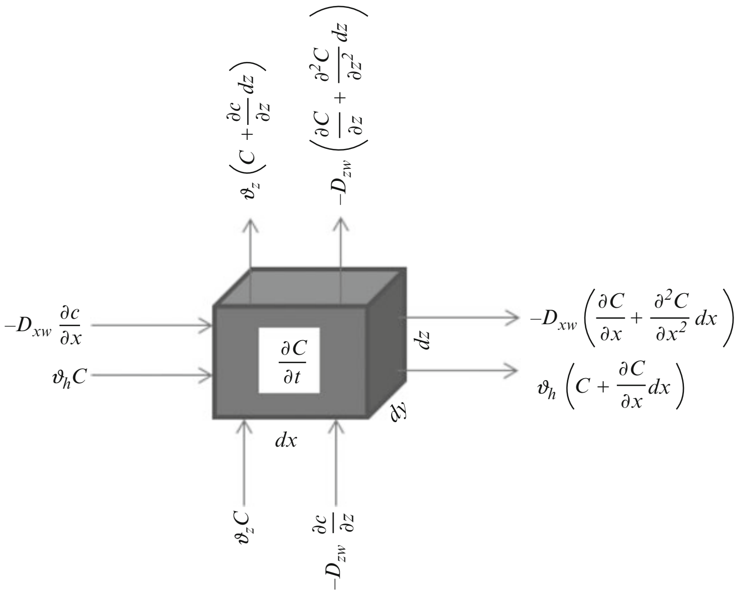


Fig. 10.4 Mass balance diagram for transport of contaminants in ground water

$$C(x,z,t=0)=0 \tag{10.6a}$$

$$\left[\upsilon_z C - D_{zw}\frac{\partial C}{\partial z}\right]_{z=z_{GWT}} = f(x) = \begin{cases} \upsilon_z g(x, z_{GWT}, t), x_1 < x < x_2 \\ 0, \text{otherwise} \end{cases} \tag{10.6b}$$

$$\frac{\partial C}{\partial x}(\pm\infty, z, t) = 0 \tag{10.6c}$$

$$\frac{\partial C}{\partial z}(x, \infty, t) = 0 \tag{10.6d}$$

where z_{GWT} = Depth of groundwater table (m), $g(t)$ = Metal concentration at the groundwater table (mg/l), and x_1, x_2 = Lateral extent over which $g(t)$ applies (m).

Initially, the ground water is assumed to be uncontaminated with any trace elements or any other elements that can affect sorption of trace elements which is indicated by Eq. (10.6a). Equation (10.6b) indicates that the amount of trace elements in the vadose zone of the soil directly above the groundwater table is equal to the amount in the ground water. Equations (10.6c) and (10.6d) indicate that the effect of diffusion and dispersion in ground water can be ignored at locations which are far away from the centreline of the pavement and the groundwater table respectively. The analytical solution to Eqs. (10.5) and (10.6) for the condition $z > z_{\mathrm{GWT}}$ is (Leij et al. 2000):

$$
\begin{aligned}
C(x,z,t) = \int_0^t \frac{\upsilon_z g(t-\tau)}{2R_w}\left[\operatorname{erfc}\left(\frac{R_w(x-x_2)-\upsilon_h\tau}{\sqrt{4R_wD_{xw}\tau}}\right)-\operatorname{erfc}\left(\frac{R_w(x-x_1)-\upsilon_h\tau}{\sqrt{4R_wD_{xw}\tau}}\right)\right] \\
\times\left[\sqrt{\frac{Rw}{\pi D_{zw}t}}\exp\left(-\frac{\left[R_w(z-z_{GWT})-\upsilon_z\tau\right]^2}{4R_wD_{zw}\tau}\right)-\frac{\upsilon_2}{2D_{zw}}\exp\left(\frac{\upsilon_z(z-z_{GWT})}{D_{zw}}\right)\right] \\
\operatorname{erfc}\left(\frac{R_w(z-z_{GWT})+\upsilon_z\tau}{\sqrt{4R_wD_{zw}\tau}}\right)d\tau
\end{aligned}
\tag{10.7}
$$

where τ is time variable.

Equation (10.7) estimates the metal concentrations that get leached from a line source at the groundwater table between points x_1 and x_2.

Class F fly ash is generally used by mixing with lime or Portland cement or cement kiln dust for stabilizing road bases. Stabilization of road bases provides the following advantages:

(i) Adds significant strength and durability to the pavement structure,
(ii) Low cost aggregates may be used and
(iii) Reduces project cost.

According to the specifications of mix design of stabilized road bases given by Federal Highway Administration of U.S. Department of Transportation, generally 2–8% lime is blended with 10–15% fly ash to produce the stabilizing agent.

Pond ash generated at KTPP is also used for stabilizing road bases in the study area. Major portion of it consists of fly ash (class F). Nine Water Leach tests (WLT) in batch mode were conducted by adopting three different proportions of pond ash, lime and soil. The proportions are given below:

Mix proportion 1–12% Pond Ash +3% Lime + Soil
Mix proportion 2–13% Pond Ash +4% Lime + Soil
Mix proportion 3–14% Pond Ash +5% Lime + Soil

The tests were conducted in accordance with the test method for shake extraction of solid waste with water (ASTM D 3987-12). Air-dried soil was crushed and the finer fraction passing through 4.75 mm IS sieve was taken for the tests. The soil was then homogeneously mixed with pond ash and lime (hydrated) at different percentages. Total 800 g of mixed samples (of each proportion corresponding to each pond ash sample) were prepared. The samples were cured in plastic bags for 7 days at 28 °C and 60% relative humidity to allow pozzolanic reactions to occur. After curing, 2.4 g of mixed samples were taken in 50 mL centrifuge tubes and 48 mL of rain water (leaching solution) was poured into them. Same L/S ratio of 20:1 was used for all the samples. The centrifuge tubes were then rotated at 29 rpm at 28 °C for 18 h. After rotation, the samples were allowed to sit for 5 min. They were then centrifuged at 3000 rpm for 20 min. After centrifugation, the suspended solid particles were filtered through 0.2 μ membrane filter papers using syringe filtration apparatus. pH of the filtered samples were noted down. They were then diluted and acidified to 2% by adding 70% concentrated HNO_3 and stored at 4 °C in refrigerator. All the samples were then analysed by 820 ICP-MS for trace elements concentrations. Same standards (as used in case of parallel extraction) were used for calibration of the instrument. Tables 10.3 and 10.4 depict different parameters and their adopted values for the simulation study.

3 Results and Discussion

3.1 Analyses of Water, Soil and Sediment Samples

3.1.1 Water Sample Analyses

Figure 10.5 shows results of trace elements analyses by ICP-MS and FS-AAS of river and ground water samples. Lanthanides and actinides were present in less than 0.01 ppm in all the five water samples. Groundwater sample 1 had As concentration of 0.008 ppm, while groundwater sample 2 had 0.001 ppm. River water samples had low As concentration (~0.002 ppm). Sc, V, Co, Rb, Y and Cd were <0.01 ppm concentration in all the samples. Cr, Ni and Ag were present in slightly higher concentrations in groundwater samples as compared to river water samples. However, in all samples the three elements were present in <0.02 ppm concentration. Concentrations of Na, Sr, Zn and Ba were higher in the groundwater samples while that of Fe and Cu were higher in river water samples. Al, Zn and Pb were found in all the samples in slightly varying concentrations. All of these elements were found in <2 ppm concentration. Ca and Mo were found in significant concentrations in groundwater samples. In river water samples, they were found in almost similar concentrations. Comparing the obtained results with the acceptable limits of the elements in drinking water as listed in Table 10.5, it can be concluded that Al and Mo exceeded both of the acceptable limits prescribed by WHO and IS 10500-2012. Ba exceeded the limit specified by IS 10500-2012. Other elements such as Fe, Cu, Zn, As, Cd, Ag, Cr, Ni and U were within acceptable limits.

Consumption of Ba in excess quantity causes high blood pressure. So, the groundwater may not be safe for drinking and it requires proper treatment to bring down the Al, Mo and Ba concentrations within acceptable limits.

Figure 10.6 shows IC analyses results of different cations and anions present in river and groundwater samples. Anions such as F^-, Cl^-, NO_2^-, SO_4^{2-} and NO_3^- and cations such as Ca^{2+} and Mg^{2+} in groundwater samples were present within WHO and IS 10500-2012 specified limits.

Comparing the concentrations of some specific elements obtained from ICP-MS analyses and of ions from IC analyses of river water samples with specified tolerance limits of them given in IS: 2296-1982, it can be concluded that river water is safe for all the types of uses according to the classification of water (A, B, C, D and E) as mentioned in Table 10.6.

Table 10.3 Subgrade and contaminant transport parameters and WLT results

						Contaminant properties				
						Initial effluent concentration from WLT (ppb)		Transport parameters		
Samples/Roadway layers	Porosity (n)	K (m/year)	LOI (%)	Bulk density (g/cc)	pH of effluent	Ba	Cr	R_d (Stabilized layer)	R_d (Subgrade)	D_d (m^2/year)
12% PA(l) + 3% Lime	0.48	69.4	0.911	1.88	11.27	2300	570	4.94	3.5	0.032
13% PA(l) + 4% Lime	0.47	80.1	0.886	1.92	11.92	1000	700	5	3.5	0.032
14% PA(l) + 5% Lime	0.45	110	0.809	1.96	12.32	700	500	4.89	3.5	0.032
12% PA(ll) + 3% Lime	0.45	41	0.964	1.86	11.19	1128	803	5.4	3.5	0.032
13% PA(ll) + 4% Lime	0.44	59.6	0.905	1.92	11.68	959	364	5.36	3.5	0.032
14% PA(ll) + 5% Lime	0.41	94	0.837	1.99	12.18	864	589	5.49	3.5	0.032
12% PA(lll) + 3% Lime	0.35	132	0.813	1.95	10.33	1593	403	5.49	3.5	0.032
13% PA(lll) + 4% Lime	0.37	142	0.809	1.97	11.17	851	334	5.76	3.5	0.032
14% PA(lll) + 5% Lime	0.35	154	0.773	2.05	11.64	590	648	6	3.5	0.032
U.S.EPA mcl						2000	100			
IS 10500–2012 Limit						700	50			
Pavement	0.07	1								
Base	0.25	3650								
Subgrade	0.48	132								

Note: R_d Retardation factor, D_d Molecular diffusion coefficient, *K* Hydraulic conductivity, *LOI* Loss on ignition

Table 10.4 Different site, aquifer and groundwater/parameters

Some site parameters	Values	Some aquifer/groundwater parameters	Values
Point of compliance (m)	20	K_{sat} (m/year)	3650
Pavement width (m)	3.75	Porosity (n)	0.3
Shoulder width (m)	2.5	Regional hydraulic gradient	0.00025
Depth to groundwater (m)	8	Horizontal dispersivity above groundwater (m)	0.192
Depth to top of stabilized layer (m)	0.125	Vertical dispersivity above groundwater (m)	0.01
Depth to bottom of stabilized layer (m)	0.3	Horizontal dispersivity in groundwater (m)	5
Infiltration rate (m/year)	1.5	Vertical dispersivity in groundwater (m)	0.1
Maximum simulation time (years)	50		

3.1.2 Assessment of Soil Contamination Due to Dumping of Pond Ash

Comparing the diffractograms of top soil samples with background soil sample (shown in Fig. 10.7) one important observation was made about the mineral Mullite. Mullite was present in all the top soil samples but it was absent in the background soil sample. It is a high temperature alteration product of aluminosilicates. This mineral is generally not found in natural soil (Lumsdon et al. 2001). On the other hand, Mullite was present in pond ash samples and is consistent with information about Mullite because pond ash is a by-product obtained after coal combustion. So presence of the mineral in the top soil of the study area might be due to wind-blown pond ash particles accumulated on soil surface. Another reason may be due to dumping of pond ash. So it can be concluded that the top soil surface of the study area is contaminated with pond ash.

Results of trace elements analyses by LA ICP-MS of the soil samples are shown in Table 10.7. For the elements such as Ti, V, Co, Ni, Zn, As, Rb, Sr, Mo, Ba, Cr, Pb, Th and U, there is a common trend (for all the samples) observed in their measured concentrations. They are present at higher concentrations in the top soil samples and concentrations decrease with depth below ground level. For other elements, no such common trend was observed. It is also seen from Table 10.7 that all the elements are present in the lands surrounding the three ash ponds in concentrations exceeding the background soil. Toxic elements such as Co, Zn, Cr, As, Pb and radioactive elements such as Th and U also leached in high concentrations during various leaching experiments on pond ash samples. So it can be concluded that the surrounding land areas of KTPP are polluted due to pond ash dumping by the plant as there is no other major industry in the area. The pond ash particles being fine might have been transported from the ash ponds and accumulated over the soil surface in the area. Over a long period of time, they may have contaminated the land areas. Wet dumping of pond ash in the study area

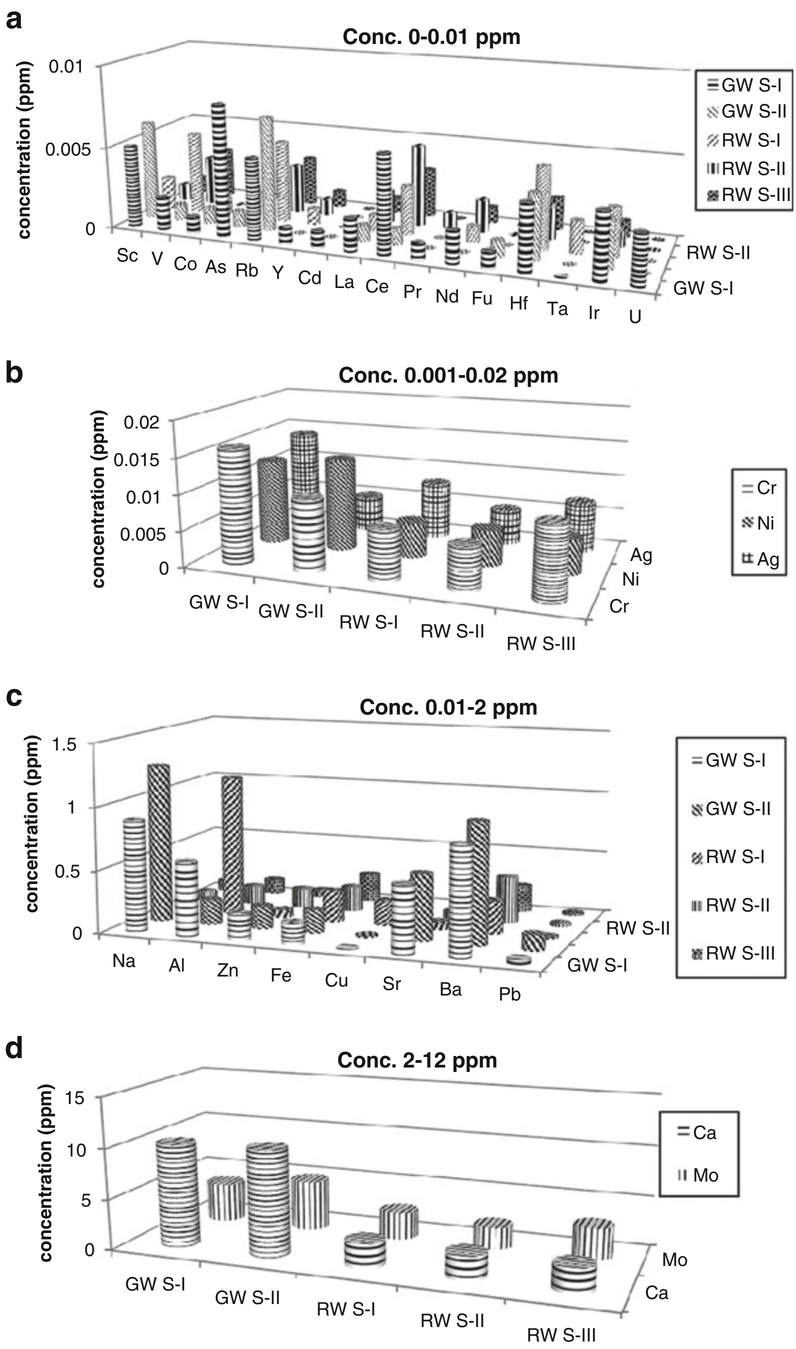


Fig. 10.5 Results of ICP-MS and FS AAS analyses of river water and groundwater samples

Table 10.5 Standards for drinking water quality

Parameters	WHO standards, mg/L (MCLs)	IS10500–2012, mg/L (Acceptable limits)
As	0.01	0.01
Ca	–	75
Mg	–	30
Ba	2	0.7
Cd	0.003	0.003
Ci (Total)	0.1	0.05
Cu	1 (SDWR)	0.05
Pb	0.015	0.01
Hg	0.002	0.001
Ni	–	0.02
Se	0.05	0.01
U	0.03	–
Pe	0.300 (SDWR)	0.3
Al	0.050-0.200 (SDWR)	0.03
Mn	0.05	0.1
Ag	0.100 (SDWR)	0.1
Mo	–	0.07
Zn	5 (SDWR)	5
F^-	4	1
Cl^-	250 (SDWR)	250
NO_2^-	1	–
SO_4^{2-}	250 (SDWR)	200
NO_3^-	10	45

Source: http://www.qpa.gov/safewater.faicLhtml and ftp://law.resource.org.mbis/S06ds.10500.2012.pdf

SDWR Secondary Drinking Water Regulations

may have also enhanced leaching of the above-mentioned elements into surrounding soil layers. So the land areas surrounding the ash ponds are already contaminated with different toxic and radioactive elements and immediate measures should be taken to save the soil environment.

3.1.3 Assessment of Sediment Contamination

XRD analysis of the single sediment sample is shown in Fig. 10.8. Graphite was present in the strongest peak. Other minerals such as berlinite, muscovite, albite, moganite and quartz could also be found in the sample. There was no major alteration observed in mineralogical compositions of the sediment sample compared to that of background soil sample. Mullite which is found in pond ash was not detected in the sediment sample.

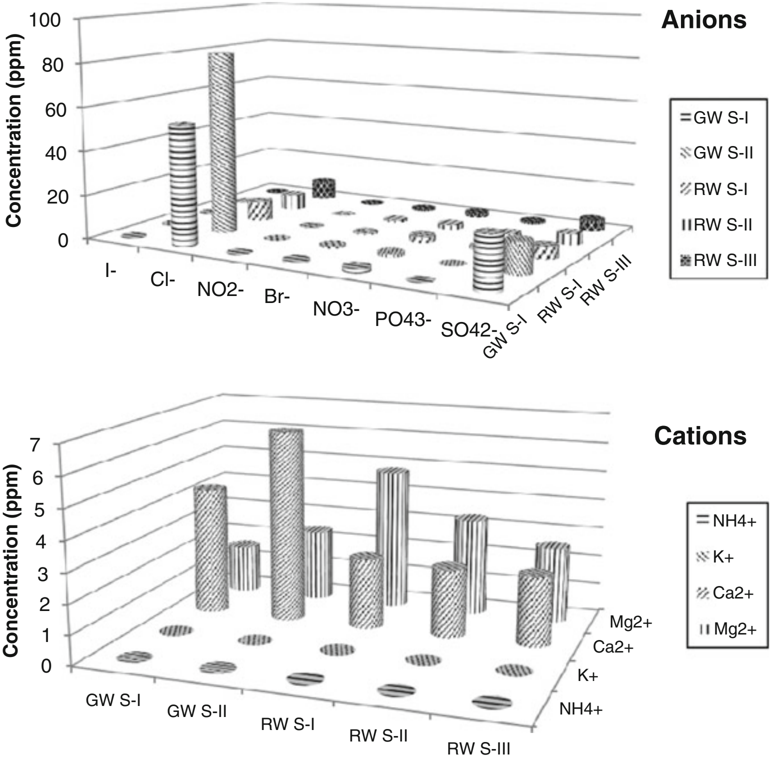


Fig. 10.6 Results of IC analyses of river water and groundwater samples (*Note: GW* Groundwater, *RW* River water, I, II and III represent sample numbers)

Table 10.6 Classification of water based on various uses as per IS: 2296-1982

Classification	Type of use
A	Drinking water source without conventional treatment but after disinfection
B	Outdoor bathing
C	Drinking water source with conventional treatment followed by disinfection
D	Fish culture and wild life propagation
E	Irrigation, industrial cooling or controlled waste disposal

Table 10.8 shows concentrations of different trace elements present in sediment (silt) sample and the same are compared with that in background soil sample. Concentrations of toxic elements such as Co, Zn, Cr, As and Pb and radioactive elements such as Th and U in the silt sample are consistently higher than their concentrations in background soil. Their concentrations are also comparable with those observed in the soil samples collected from surrounding areas of ash ponds in the study area. So, the river bed is contaminated which may have occurred due to pollutant load coming from KTPP (either by air or by effluent discharge) because

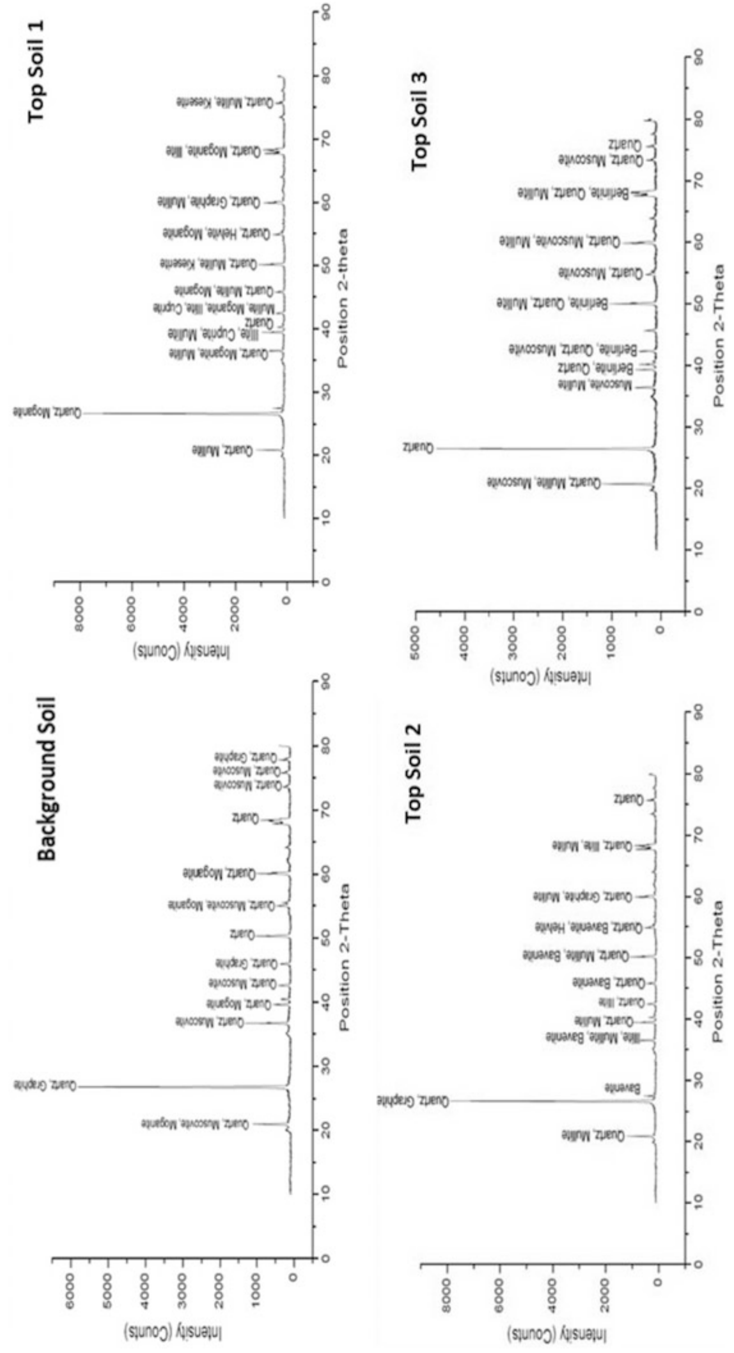


Fig. 10.7 XRD analyses results of soil samples

Table 10.7 Results of analyses of soil samples by LA ICP-MS

Conc. (ppm) in soil sample 1					Conc. (ppm) in soil sample 2				Conc. (ppm) in soil sample 3				Conc. in background soil (ppm)
Elements	Top	25 cm	50 cm	75 cm	Top	25 cm	50 cm	75 cm	Top	25 cm	50 cm	75 cm	
Li	14.2	26	83.06	46.41	22.8	32.09	53.08	17.41	32.36	35.17	44.49	36.51	7.49
Sc	6.22	9.16	30.11	13.62	20.52	13.48	15.82	8.66	13.76	11.93	19.28	12.75	4.51
Ti	7017.76	3456.39	2627.49	1505.07	7854.18	6904.6	2674.37	1676.59	6979.77	3213.79	2763.68	2637.31	640.85
V	164.13	63.37	45.41	28.5	95.48	76.66	48.86	46.63	63. 25	44.09	37.51	36.79	9.19
Co	15.99	13.75	7.92	2.72	14.25	8.52	7.04	5.95	12	10.28	5.65	2.41	1.02
Ni	75.27	36.42	22.88	18.42	40.09	34.28	33.39	25.61	161.19	34.96	27.4	20.97	8.34
Zn	66.25	62	41.64	31.46	70.54	49.2	48.45	45.82	55.94	54.57	37.53	19.21	6.69
As	4.93	3.65	2.91	0	3.3	2.77	1.57	3.3	11.2	4.89	3.93	2.78	0
Rb	147	94.98	86.73	34.79	77.67	70.94	58.57	34.84	109.4	64.72	64.06	33	12.4
Sr	94.62	35.13	23.28	5.82	52.63	36.1	24.86	12.91	40.53	39.53	9.18	7.37	6.08
Y	2.75	40.6	31.07	11.36	17.14	6.18	14.72	5.64	6.04	5.61	11.73	15.5	1.5
Zr	13.7	81.41	103.21	291.23	323.52	23.6	95.43	22.4	29.91	56.34	33.26	89.67	6.25
Mo	9.36	4.43	2.47	1.54	9.53	5.24	3.84	2.35	10.03	6.56	3.65	1.29	0.185
Ag	6.21	6.42	3.48	1.42	2.74	0.621	0.425	0.152	3.21	2.48	2.29	1.75	0.019
Ba	659.33	504.41	471.18	303.05	414.43	366.51	204.39	141.33	205.27	171.27	93.82	73.37	18.19
Cr	115.48	108.65	103.68	98.65	121.56	106.87	102.68	84.65	114.65	106.38	93.65	86.65	10.68
La	5.25	11.75	34.02	12.21	10.19	8.6	27.21	11.33	9.86	5.75	28.16	12.43	2.29
Ce	7.63	23.24.	114. 15	28.02	17.75	18.1	68.4	24.74	24.26	5.94	53.57	25.23	2.78
Pr	1.44	2.55	7.45	3.22	2.67	2.03	5.62	2.49	2.62	1.33	6.18	2.74	0.55
Nd	4.45	9.14	27.38	12.15	10.64	7.48	19.19	8.4	9.47	5.05	22.93	9.81	2.03
Sm	0.5	2.4	5.52	2.61	2.51	1.41	3.83	1.59	1.85	1.02	4.08	2.23	0.39
Eu	0.198	0.75	1.37	0.68	0.81	0.361	0.79	0.336	0.37	0.234	0.72	0.48	0.098
Gd	1.09	3.42	8.25	3.45	4.61	2.55	5.42	1.47	3.54	1.43	7.47	3.18	0.44

(continued)

Table 10.7 (continued)

Conc. (ppm) in soil sample 1					Conc. (ppm) in soil sample 2				Conc. (ppm) in soil sample 3				Conc. in background soil (ppm)
Elements	Top	25 cm	50 cm	75 cm	Top	25 cm	50 cm	75 cm	Top	25 cm	50 cm	75 cm	
Tb	0.151	1.07	1.2	0.5	0.64	0.29	0.66	0.232	0.328	0.179	0.72	0.45	0.051
Dy	0.54	8.02	5.65	2.23	2.82	1.09	2.78	1.12	1.24	0.92	2.47	2.55	0.223
Ho	0.108	1.69	1.1	0.436	0.58	0.226	0.55	0.233	0.216	0.202	0.44	0.54	0.05
Er	0.365	5.05	3.43	1.53	2.14	0.83	1.69	0.71	0.83	0.74	1.71	1.68	0.159
Tm	0.054	0.74	0.398	0.208	0.283	0.101	0.202	0.09	0.095	0.11	0.163	0.239	0.0174
Yb	0.427	5.2	2.73	1.55	2.3	0.7	1.46	0.84	0.79	0.8	1.39	1.82	0.124
Lu	0.0502	0.65	0.373	0.219	0.3	0.094	0.191	0.095	0.099	0.121	0.183	0.265	0.019
Hf	0.456	2.62	2.71	5.82	7.13	0.64	2.38	0.82	0.84	1.85	0.89	2.39	0.14
Ta	0.397	0.81	1.25	0.79	5.83	0.56	1.45	0.53	0.45	1.32	0.66	0.56	0.089
Pb	19.05	17.53	15.95	15.4	28.74	14.76	11.78	10.79	18.03	17.44	12.09	5.44	2.17
Th	3.67	2.51	1.85	0.84	5.33	4.72	2.13	0.25	1.53	0.52	0.18	0.14	0.06
U	3.5	2.74	2.1	0.94	1.65	1.05	1.02	0.34	2.28	1.72	1.09	0.88	0.148

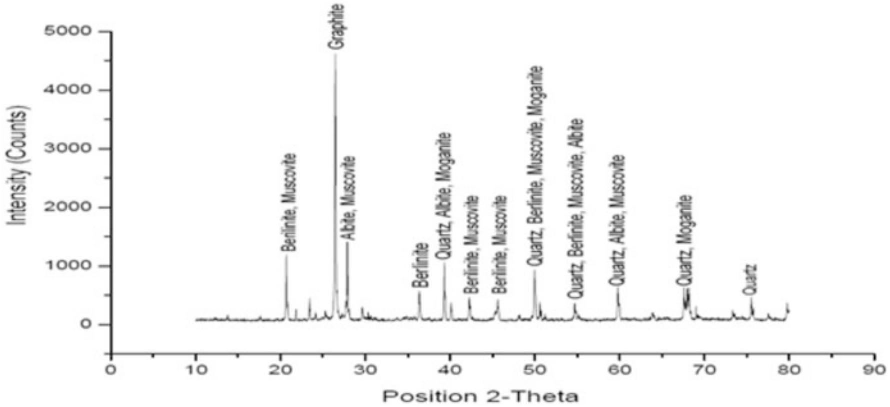


Fig. 10.8 Mineralogical composition of sediment sample

there is no major industry on the upstream of the river. Part of the contaminant load coming into the river may be diluted (due to flow of the river water) and the remaining precipitated on the river bed. Concentration factors (concentration in river sediment to concentration in background soil) of most of the elements were less than 10 except for Co (24.41), Zn (14.30) and Pb (12.94). Minimum concentration factor was observed for Rb (1.56) and maximum for Co (24.41). Accumulation of contaminants over time might have increased the level of contamination in the river bed as shown in Table 10.8.

3.2 *WQI and DRASTIC Approaches*

3.2.1 Water Quality Index for Assessing River Water Quality

According to Table 10.9, average value of WQI of Rupnarayan river water is 62.1 which lies between 51 and 70 range. According to the Chart for Rating River Water Quality as mentioned in Table 10.2, the river water quality can be classified as Medium category.

3.2.2 "DRASTIC" Index for Assessing Groundwater Pollution Vulnerability

In the present study, Drastic Index value was calculated for groundwater in Kolaghat surrounding the Kolaghat Thermal Plant area taking different values of the factors from the GIS-based studies done by Shahid (2000) and Chowdhury et al. (2009) in the district of Midnapur. The rating of the factors and the weights of the

Table 10.8 Results of trace elements analyses of silt samples by LA ICP-MS

Elements	Conc, in silt (ppm)	Conc, in background soil (ppm)
Li	34.91	7.49
Sc	18.67	4.51
Ti	2706.22	640.85
V	66.31	9.19
Co	24.9	1.02
Ni	46.23	8.34
Zn	95.7	6.69
As	2.54	0
Rb	19.35	12.4
Sr	31.55	6.08
Y	5.71	1.5
Zr	13.59	6.25
Ag	0.176	0.019
Ba	171.5	18.19
Cr	76.66	10.68
La	4.53	2.29
Ce	9.36	2.78
Pr	2.81	0.55
Nd	4.02	2.03
Sm	1.29	0.39
Eu	0.25	0.098
Gd	1.2	0.44
Tb	0.191	0.051
Dy	1.44	0.223
Ho	0.23	0.05
Er	0.67	0.159
Tm	0.097	0.0174
Yb	1	0.124
Lu	0.097	0.019
Hf	0.35	0.14
Ta	0.63	0.089
Pb	28.07	2.17
Th	0.46	0.06
U	0.96	0.148

factors were taken from Canter (1996). Table 10.10 shows different parameters that were considered for calculating DI value.

Based on the above values, DI value for the best condition of groundwater (i.e., zero pollution potential) is 28 while considering the worst condition of groundwater (i.e. highest pollution potential) would result in a DI value of 226. The value of DI (170) obtained for this study is closer to the highest possible value.

Table 10.9 Details of WQI parameters of Rupnarayan river water

Parameters	Measured values			Average measured values	Subindex value (S_i)	Weighting S_iW_i factor (W_i)	
DO (% Saturation)	76	78	71	75	74	0.17	12.58
FC (cfu/100 ml)	33,600	32,400	35,600	33,867	6	0.15	0.9
pH	7.23	7.15	7.38	7.25	94	0.12	11.28
BOD_5(mg/L)	1.6	1.9	2.1	1.867	77	0.1	7.7
NO_3^-(mg/L)	2.647	2.165	2.154	2.322	85	0.1	8.5
PO_4^{3-}(mg/L)	1.374	1.4	1.099	1.291	38	0.1	3.8
ΔT (°C)	0.7	0.9	1.2	0.93	87	0.1	8.7
Turbidity (NTU)	27.2	35.4	34.9	32.500	48	0.08	3.84
TS (mg/L)	320	289	310	306	60	0.08	4.8
Total (WQI)							62.1

Table 10.10 Different parameters related to calculation of DRASTIC Index (DI)

Factors	Range of valuesfor factors	Ratings (R_i)	Weights (W_i)	R_iW_i
Depth to groundwater	5–15 m	9	5	45
Recharge rate of aquifer	More than 10 inches/year	9	4	36
Aquifer media	Medium to coarse sand with gravel	8	3	24
Soil media	Clay loam	3	2	6
Topography	0–2%	10	1	10
Impact of the vadose zone	Clay Silty	5	5	25
Hydraulic conductivity of aquifer	1000–2000 gpd/ft^2	8	3	24
Total (DI)				170

This indicates that groundwater in the area surrounding the Kolaghat Thermal Power Plant is vulnerable to pollution.

3.3 Contaminant Transport Modelling Using WiscLEACH 2.0 Software

Increase in lime content caused an increase in pH levels of the effluent solutions during batch Water Leach Tests (WLTs). Initial effluent concentration (C_0) of Ba decreased with lime addition indicating its cationic leaching pattern, i.e., greater leaching at acidic pH. In case of Cr, different samples showed different leaching patterns.

Contour graphs of equal concentrations predicted by WiscLEACH show concentration distributions of two metals Ba and Cr at different years (1, 10 and 50 years after their first leaching) in the soil vadose zone and ground water. Since concentration trends for all three samples: PA1, PA2 and PA3 were similar, concentration distributions for one sample (PA1) are shown in Figs. 10.9 and 10.10.

Effluent concentrations (ppb) of Ba and Cr from batch Water Leach Test on pond ash-soil-lime mixtures were taken as initial effluent concentration (C_0). It can be seen that maximum concentrations of Ba and Cr after 1 year were within vadose zone much above groundwater table. After 10 years, maximum concentrations of the metals were found slightly above the vadose zone-groundwater table interface. After 50 years, maximum concentrations of the same shifted into groundwater zone. So it is clear from the contour graphs that the metals (Ba and Cr) gradually got transported into the groundwater zone over time. WiscLEACH numerical simulations suggest that the metal concentrations decreased over time and distance. It is due to adsorption and dispersion of these metals in the soil vadose zone and subsequent dissolution in ground water.

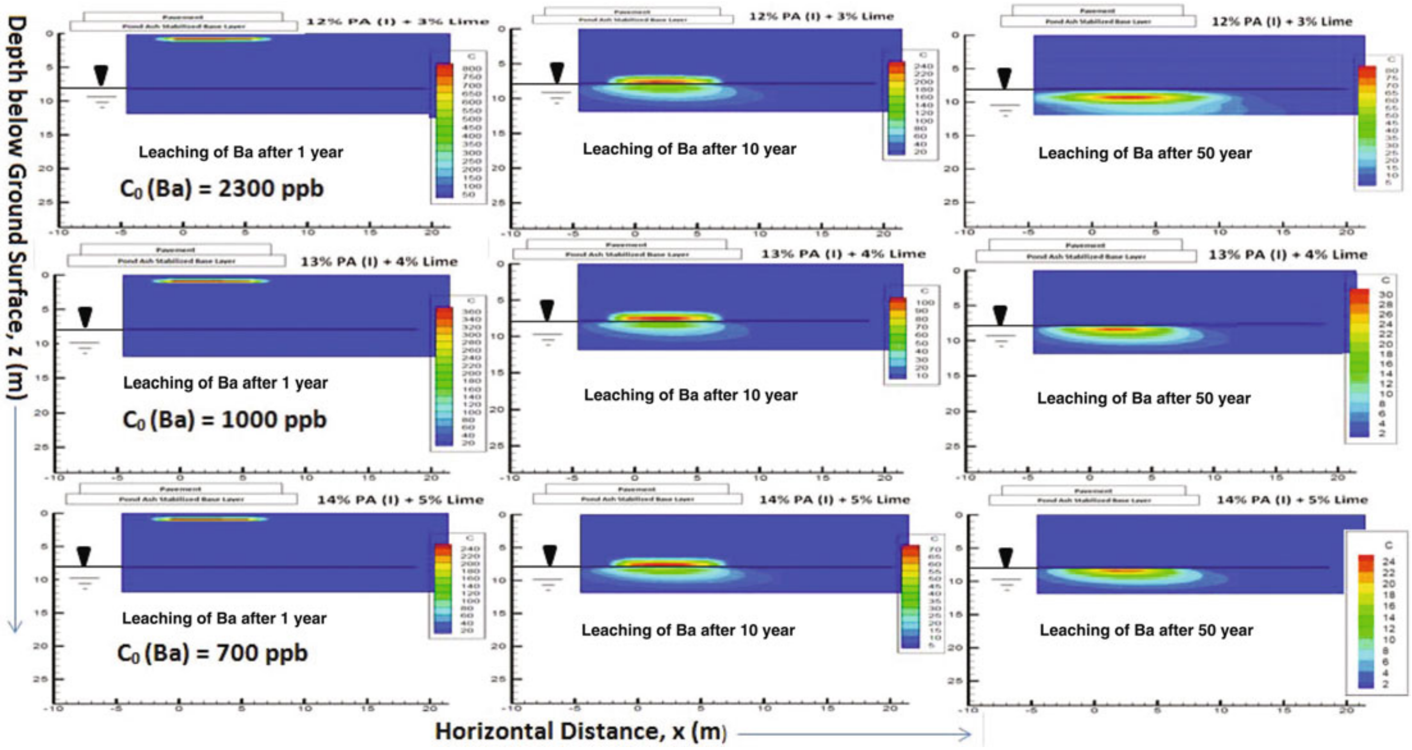


Fig. 10.9 Predicted Ba concentrations in vadose zone and ground water for PA 1

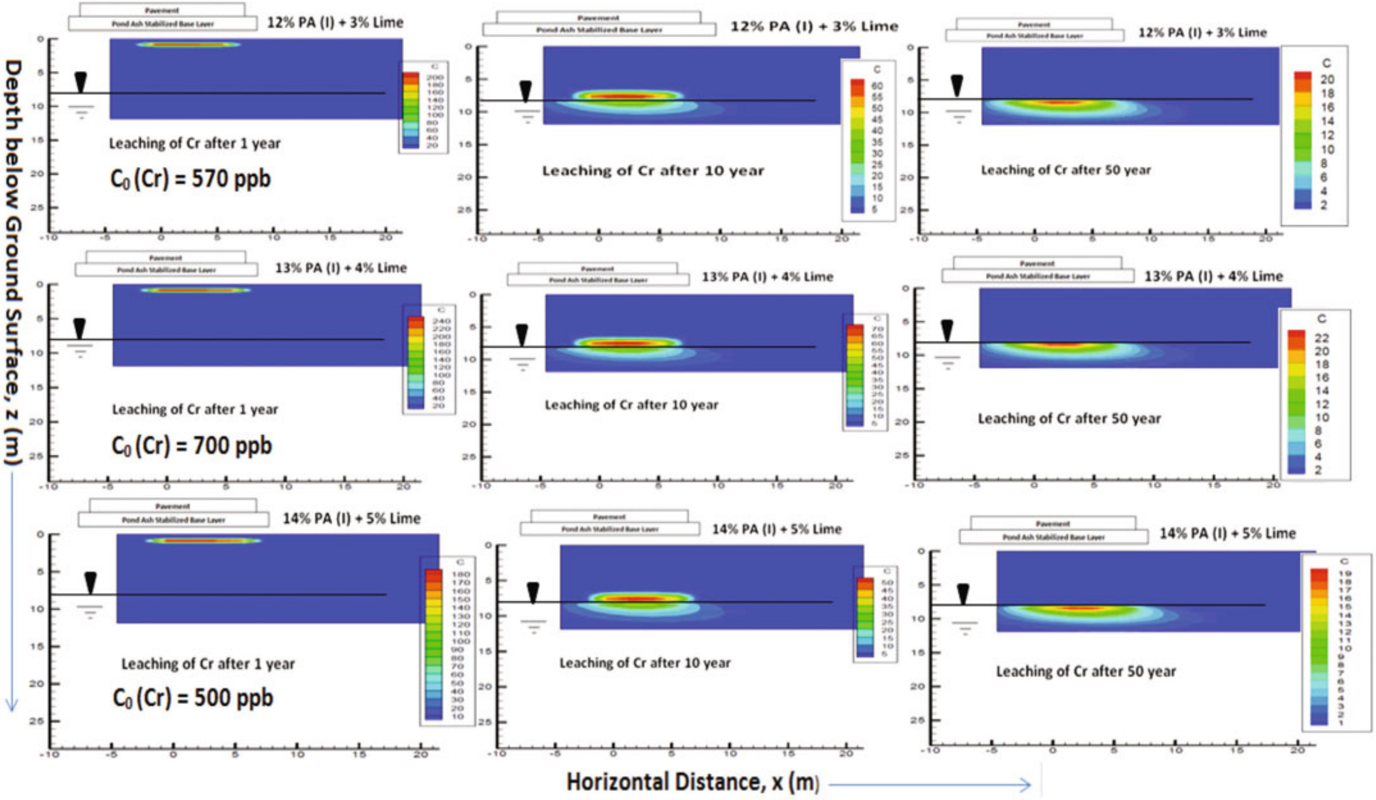


Fig. 10.10 Predicted Cr concentration in vadose zone and ground water for PA 1

As per standards for drinking water recommended by WHO, MCLs for Ba and Cr are 2000 and 100 ppb respectively. IS: 10500-2012 recommends acceptable limits for these two contaminants in drinking water to be within 700 and 50 ppb, respectively. Leaching of Ba from pond ash stabilized base layers into ground water (for all the time periods considered) did not exceed WHO and IS 10500-2012 recommended limits for drinking water. Contour plots of leaching of Cr drawn for 10 years show that its concentrations in groundwater exceeded the IS 10500-2012 recommended limit for drinking water. However, concentrations of the same in ground water at 50 years were within the limit.

ICP-MS analyses of groundwater samples of the study area indicated presence of Ba in exceedance of the limit specified by IS 10500-2012 for drinking water. However, Cr was present within the specified limit. So, values of Cr concentrations in ground water predicted for a 50-year time period) by WiscLEACH simulations are similar to ICP-MS results while simulated Ba concentrations are contrary to them.

4 Conclusions

Environmental impacts of open fly ash dumping were quantified using WQI, DRASTIC and WiscLEACH modelling.

(i) WQI for Rupnarayan river was found to be 62.1 based on analyses of three river water samples near KTPP indicating that the river hasmedium water quality. River water is suitable for all purposes of uses as mentioned in IS: 2296-1982.

(ii) A DRASTIC value of 170 was determined based on the 2 groundwater samples tested indicating that the ground water in the study area is vulnerable to pollution. Further, ground water in this area may not be safe for drinking purposes and it requires proper treatment before drinking to reduce concentrations of Al, Mo and Ba. These elements were in exceedance of their acceptable limits prescribed by WHO and IS-10500 for drinking water.

(iii) XRD analyses of the soil samples showed the presence of mullite, a mineral that is normally not found in natural soil (background soil). It was found in all pond ash samples and all top soil but not deep soil samples collected from around KTPP. So it can be concluded that the top soil in the study area is contaminated by pond ash. Trace elements analyses of the soil samples indicated serious contamination in surrounding areas of ash ponds with different toxic and radioactive elements.

(iv) There was no major alteration in the mineralogical composition of the sediment sample compared to that observed in the background soil sample. Results of trace elements analyses of the sediment sample indicated that toxic elements such as Co, Zn, Cr, As and Pb and radioactive elements such as Th and U were present in higher concentrations compared to that observed in the background soil sample.

(v) Batch Water Leach Test results on pond ash-soil-lime mixtures indicated that initial effluent concentration (C_0) of Ba decreased with lime addition. Contour graphs predicted by WiscLEACH suggested that concentrations of Ba and Cr decreased over time and distance. It is due to adsorption and dispersion of these metals in the soil vadose zone. Fifty years after the contaminants first leached, both Ba and Cr concentrations in ground water were observed to be within WHO and IS 10500-2012 recommended limits for drinking water. However, ICP-MS analyses of groundwater samples of the study area indicated presence of Ba in exceedance of the limit specified by IS 10500-2012 for drinking water, while Cr was present within the specified limit. So predicted values of Cr concentrations in ground water (at 50-year time period) by WiscLEACH simulations are similar to the ICP-MS results, while simulated Ba concentrations are contrary to them.

References

ASTM D3987–12, Standard Practice for Shake Extraction of Solid Waste with Water.

Aydilek, D.A. and Cetin, D.B., 2013. Geoenvironmental impacts of using high carbon fly ash in structural fill applications, Research report. Maryland Dept. of Transportation, 1–265, downloaded from http:\crwww.roads.maryland.gov/OPR_Research/MD-13-SP909B4P-Geoenvironmental-Impacts-Of-Using-HCFA-In-Structural-Fill-Applications.pdf.

Canter, L.W., 1996. Environmental Impact Assessment (Second Edn.). McGraw-Hill International Editions.

Cetin, B., Aydilek, A.H. and Li, L., 2012. Experimental and numerical analysis of metal leaching from fly ash-amended highway bases. *Waste Management*, **32(5)**, 965–978.

Chowdhury, A., Jha, M.K., Chowdary, V.M. and Mal, B.C., 2009. Integrated remote sensing and GIS based approach for assessing groundwater potential in West Medinipur district, West Bengal, India. *International Journal of Remote Sensing*, **30(1)**, 231–250.

IS 10500: 2012. Indian Standard Drinking Water – Specification (Second Revision).

Leij, F.J., Priesack, E. and Schaap, M.G., 2000. Solute transport modeled with Green's functions with application to persistent solute sources. *Journal of Contaminant Hydrology*, **41(1–2)**, 155–173.

Lumsdon, D., Meeussen, J.C., Paterson, E., Garden, L. and Anderson, P., 2001. Use of solid phase characterisation and chemical modelling for assessing the behaviour of arsenic in contaminated soils. *Applied Geochemistry*, **16(6)**, 571–581.

Pang, L., Close, M., Schneider, D. and Stanton, G., 2002. Effect of pore-water velocity on chemical nonequilibrium transport of Cd, Zn, and Pb in alluvial gravel columns. *Journal of Contaminant Hydrology*, **57(3–4)**, 241–258.

Perfect, E., Sukop, M.C. and Haszler, G.R., 2002. Prediction of Dispersivity for Undisturbed Soil Columns from Water Retention Parameters. *Soil Science Society American Journal*, **66**, 696–701.

Shahid, S., 2000. A Study of Groundwater Pollution Vulnerability Using DRASTIC/GIS, West Bengal, India. *Journal of Environmental Hydrology*, 8, 1–9.

Woumeni, R.S. and Vauclin, M., 2006. A field study of the coupled effects of aquifer stratification, fluid density, and groundwater fluctuations on dispersivity assessments. *Advances in Water Resources*, **29(7)**, 1037–1055.

Chapter 11
Degradation of Plastics

Bijlee Nithin and Sudha Goel

1 Introduction

Today, plastics are an integral part of modern society. Living without plastics is almost impossible ever since their mass production began in the 1950s (Barnes et al. 2009). Plastics are versatile materials mainly due to their molecular structure and additives, and have many different positive applications that have eased human life to a great extent. However, plastics are a major treatment and disposal problem in urban solid waste management as plastics are relatively inert and non-biodegradable (Nayak and Tiwari 2011). It is an undeniable fact that the environment and its biodiversity is greatly disturbed and damaged as a result of the rampant and uncontrolled use and disposal of these non-biodegradable materials (Barnes et al. 2009; Teuten et al. 2009). The impact of plastics on the environment is now a global concern since treatment and disposal methods are limited while rates of production and usage are increasing. Incineration of these plastic wastes generates toxic and harmful gases causing air pollution and is a common practice in many less developed and developing countries as appropriately engineered/planned landfill sites to dispose these wastes are very limited. Additionally, many disposal methods that are not acceptable like open dumping, uncontrolled incineration, unscientific composting and improper landfilling are often followed in countries like India (Kandakatla et al. 2012). Increasing concern among people about this problem has stimulated interest in the field of biodegradation of polymers such as polyethylene and polystyrene, etc., which are very stable in nature, and are not readily

---

B. Nithin
Coal India Limited, Dist. Burdwan, 713 332 Kolkata, West Bengal, India

S. Goel (✉)
Civil Engineering Department, Indian Institute of Technology Kharagpur,
Kharagpur 721302, WB, India
e-mail: sudhagiitkgp@gmail.com

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_11

biodegradable. Globally, about 140 million tonnes of synthetic polymers are produced every year (Masayuki 2001) and only about 10% of these materials are recycled or reused as the disposal options are extremely limited.

1.1 History of Plastics

Plastics are a product of the twentieth century. The word 'plastics' is derived from a Greek word "*plastikos*" which means "able to mould into different shapes". Elements contained in the plastics that we use in our daily lives include C, Si, H, N, O and Cl (Seymour 1989).

Originally, plastics were created to substitute and replace natural products like Lacquer, Shellac, Amber, Shells, etc. as plastics are largely synthetic materials made from non-renewable resources such as crude oil, coal and natural gas (Augusta et al. 1993).

1.2 Plastics and Their Uses

"Plastics are defined as those polymers which become mobile on heating and thus can be cast into moulds. Plastics are non-metallic mouldable compounds and the material made from them, can be pushed into almost any desired shape" (Seymour 1989). Several different grades of plastics are now available and new ones continue to be formulated.

1.3 Polymers and Their Structures

Polymers commonly in use in every-day life are Polyethylene, Polypropylene, Polyester, Polyvinyl Chloride, Polyurethane, Poly (ethylene terephthalate), and Nylon (Fig. 11.1).

Plastics are being used in every sector of domestic, industrial and non-industrial activities. They are a major part of the economy and infrastructure and have applications in agriculture, building and construction, telecommunication, consumer goods, packing, health and medicine. Innumerable goods from various industries are manufactured using plastics. A few examples include computers and printers, stationery, plastic furniture, packaging materials for food, water, toiletries, and other goods, automobile components, water tanks, water pipes and fittings (Fig. 11.2).

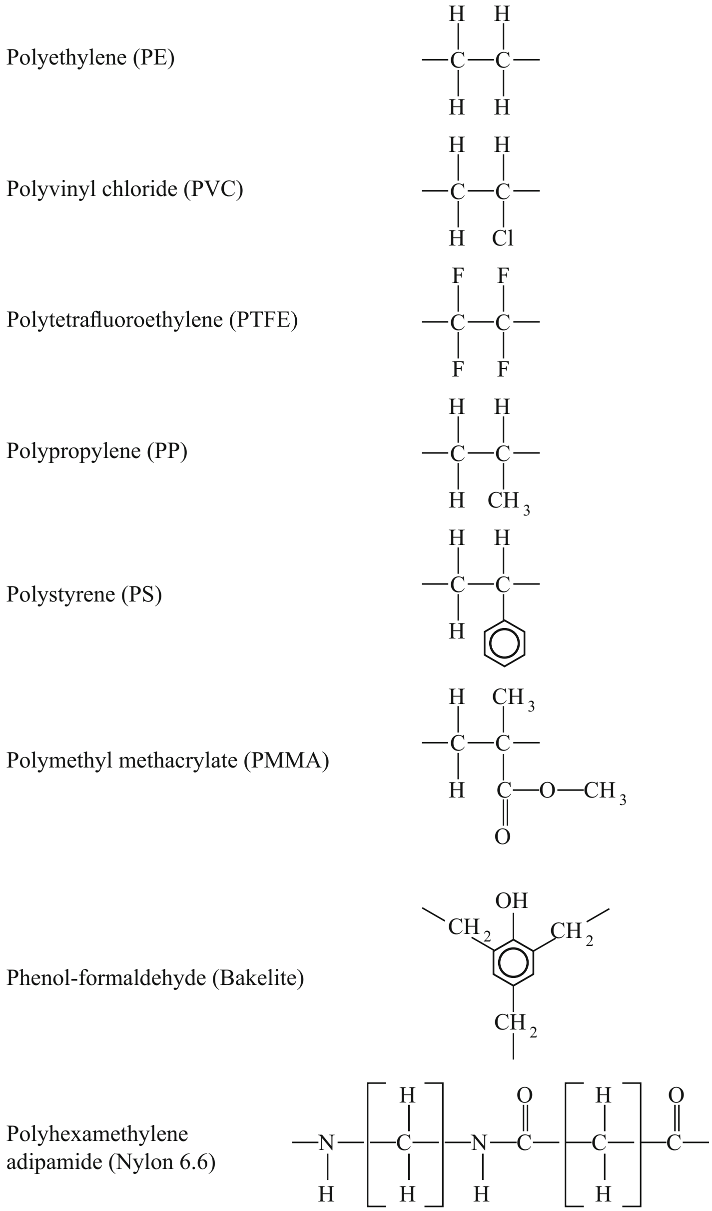


Fig. 11.1 Structures of different polymers

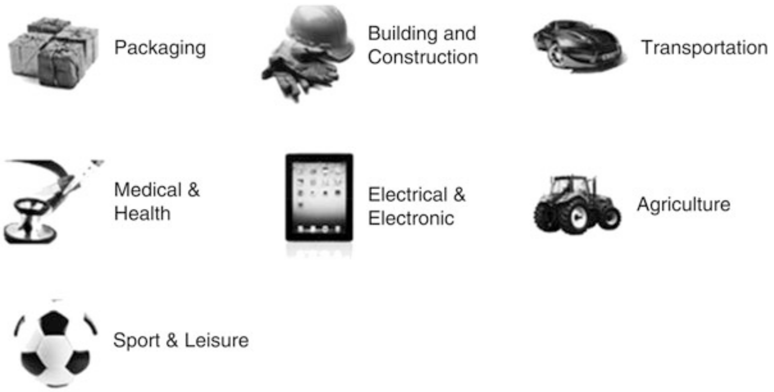


Fig. 11.2 Plastics play a vital role in major sectors of the economy

Table 11.1 Sector-wise utilization of plastic in India and globally

Sector-wise	India	Global
Packaging	43	35
Infrastructure	21	25
Automobiles	16	17
Agriculture	2	8
Others	18	15

Source: FICCI (2014)

1.4 Plastic Waste Generation

In the United States alone in 2010, 12.4% (31 million tons) of the total MSW in the country was plastic waste. Of this, 14 million tons of plastic waste was containers and packaging, 11 million tons were durable goods like household appliances, and about 7 million tons were non-durable goods, e.g., disposable food plates and drinking cups. Out of the total plastic waste generated, only 8–12% of it was recovered for recycling and included sacks, wraps and bags which were recycled. Recycling of plastics used in automobiles is not accounted for in the MSW recycling rate (USEPA 2012).

Per capita consumption of plastic in India was 9.7 kg/person-year while it was 109 kg/person-year in the USA followed by 65, 45, and 32 kg/person-year in Europe, China, and Brazil (FICCI 2014). Sector-wise comparison of plastic usage in India and globally is provided in Table 11.1. Bulk of the plastic generated in India is used for packaging and is least in the agriculture industry.

Currently, 3.6 million tons/year of plastic are recycled and the plastic recycling industry provided employment to about 1.6 million people of which 0.6 million are employed directly, and the other 1 million indirectly (FICCI 2014).

Mutha et al. (2006) found a direct, exponential relationship between a country's per capita gross domestic product (GDP) on a purchasing power parity (PPP) basis and plastic consumption using data from 33 countries including India (coefficient of correlation = 0.85). They developed a model to estimate future plastics consumption and found that total plastics consumption in India may increase by a factor of six between 2000 and 2030. The weighted average lifetime of plastic products was calculated to be 8 years. Given these data, it is clear that plastic waste generation will continue to increase exponentially in the near future.

1.4.1 Environmental Impacts of Plastic Waste

Plastic wastes are now ubiquitous all over the globe and can be found in marine and other aquatic environments, in soils and sediments, and in landfills. The harmful effects of plastic waste in the environment have been reviewed by several researchers and are summarized here:

(i) Plastics have been found littering animal habitats and in the stomachs of animals (Barnes et al. 2009). The number of microscopic plastic fragments (20 micron diameter) has been increasing steadily since the 1960s and is attributed to shredding and grinding of plastic waste prior to disposal. The long-term effects of these microscopic particles on ecosystems are still not clear.

(ii) Toxic, hydrophobic contaminants present in the environment, especially aquatic environments, tend to adsorb to any plastics in the environment. This increases the bioaccumulation potential of the toxic contaminants since their transfer from plastics to organisms becomes easier (Teuten et al. 2009).

(iii) Natural degradation of these polymeric plastics will result in smaller fragments and monomeric residues. Plasticizer, additives, monomeric residues can leach from landfills, soils and sediments into surface and ground water resources resulting in large-scale contamination (Teuten et al. 2009). Some plasticizers, and additives like Bisphenol-A (BPA), an endocrine-disrupting chemical, was detected in the landfill leachates of tropical Asian countries and Japan in the range from 180 ng/L to 4.3 mg/L. This was five orders of magnitude higher than concentrations in sewage. Half of the estrogenic activity of the leachates could be attributed to BPA.

(iv) Lately, degradable plastics are being sold in developed countries with the assumption that they will degrade more quickly than conventional plastics. However, their visual disappearance at a more rapid rate is no indication that they may be benign in their impact on the environment. The end products of their metabolism and their potential for bioaccumulation and endocrine-disruption remain to be evaluated (Roy et al. 2011).

2 Degradation of Plastics

By conventional wisdom, plastics are considered to be biologically and chemically inert materials that can remain stable in the environment for tens to hundreds of years. However, degradation of these relatively inert materials does occur in the natural environment depending on the availability of several environmental factors such as sunlight or UV light, heat, pH conditions, nutrient availability (including oxygen) and microbes capable of biodegrading these polymers. Physical and chemical properties of the plastic polymers also affect their degradation in the environment. These properties include their size, and their chemical and molecular structure.

Three major mechanisms for degradation of plastics are shown in Table 11.2 along with the factors influencing degradation. The first two types of degradation mechanisms are abiotic and the last one is biotic in nature. Plastics can be degraded abiotically and/or biotically as described in this section.

2.1 *Abiotic Degradation*

Abiotic degradation includes exertion of intra-molecular modifications in the polymer by physical and/or chemical process (Sivan 2011). The result of these processes may be fragmentation and size reduction, lower molecular weights of polymers, decrease in tensile strength of the material and their visual disappearance (Roy et al. 2011). Abiotic degradation is often an important preliminary step for biotic degradation to take place since it helps to convert inert material to more biodegradable forms.

Table 11.2 Routes for the degradation of plastic (Shah et al. 2008)

Factors (requirement/ activity)	Photo-degradation	Thermo-oxidative degradation	Biodegradation
Active agent	UV-light or high-energy radiation	Heat and oxygen	Microbial agents
Requirementof heat	Not required	Higher than ambient temperature required	Not required
Rate of degradation	Initiation is slow, but propagation is fast	Fast	Moderate
Other considerations	Environment friendly if high-energy radiation is not used	Environmentally not acceptable	Environment-friendly
Overall Acceptance	Acceptable but costly	Not acceptable	Cheap and acceptable

Various strategies have been used for improving the degradability of polymers like polyethylene and include modification of the polymer structure by introducing weak sites (functional groups such as carbonyl group), hydrolysable linkages and use of pro-oxidants and metal-organic complexes in these polymers (Roy et al. 2011). The pro-oxidants (photo-sensitizers) in synthetic polymers are also known as oxo-biodegradable polymer compounds. Using metal oxides as catalysts, the photodegradation of low density polyethylene (LDPE) and polypropylene (PP) films can be activated. This results in reduction of molar mass and formation of readily biodegradable oxygenated groups (such as carbonyl). These materials are more easily degraded under oxidative conditions and saturated humidity as compared to natural humidity (Singh and Sharma 2008). Other factors that can enhance degradation of plastics include the use of catalysts, ozone, autoclaving of plastics, and mechanical stress.

The effect of autoclaving on the carbon and oxygen content of plastics is summarized in Table 11.3 (Nithin 2013). The carbon content of both grades of plastics tested decreased after autoclaving while the oxygen content increased after autoclaving. These results indicate partial oxidation of plastic polymers after autoclaving. Illustrative examples showing change in structure (morphology) of plastics before autoclaving and after autoclaving and incubation with bacteria are shown in Fig. 11.3 (Nithin 2013).

Table 11.3 Energy dispersive x-ray diffraction results showing changes in composition of plastic samples after autoclaving

Description of sample	Carbon, %	Oxygen, %
Grade 1 without autoclave	98.82	1.18
Grade 1 autoclave	91.67	8.33
Grade 2 without autoclave	95.97	4.03
Grade 2 autoclave	90.11	9.89

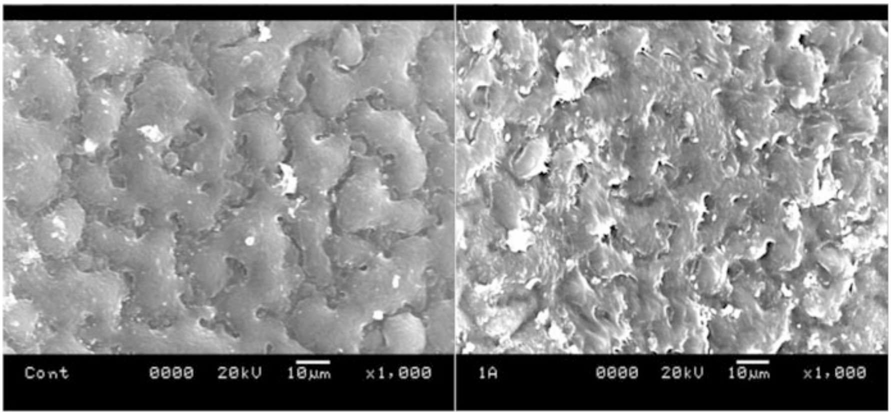


Fig. 11.3 Scanning electron micrographs (SEM, 1000×) of Grade 1 plastic. *Left*: Original plastic; *Right*: After autoclaving and incubating with bacterial inocula for 34 days (Nithin 2013)

2.2 Biodegradation

Biodegradation of polymers occurs through various mechanisms: solubilisation, dissolution, hydrolysis and enzyme-catalysed degradation (Singh and Sharma 2008).

Biotic degradation or biodegradation of plastic can occur under aerobic or anaerobic conditions.

(i) *Aerobic biodegradation or respiration*: This is an important process in the natural attenuation of contaminants at many hazardous waste sites where aerobic bacteria use oxygen as an electron acceptor and breakdown organic plastic into final products of carbon dioxide (CO_2) and water (Nayak et al. 2011):

$$C_{plastic} + O_2 \rightarrow CO_2 + H_2O + C_{residual} + \text{Biomass}$$

(ii) *Anaerobic biodegradation*: Anaerobic biodegradation is also an important process in the natural attenuation of contaminants at many hazardous waste sites where microorganisms break down organic contaminants in the absence of oxygen. There are two possible pathways for anaerobic biodegradation: anaerobic respiration and fermentation. When anaerobic bacteria use nitrate, sulphate, Fe, Mn, and CO_2 as their terminal electron acceptors, the process is anaerobic respiration. Plastics can be biodegraded by fermentation when the organic material (including plastic) serves as both, electron donor and acceptor resulting in the production of smaller simple organic compounds (Nayak et al. 2011) as shown below.

$$C_{plastic} \rightarrow CH_4 + CO_2 + H_2O + C_{residual} + \text{Biomass}$$

2.2.1 Factors Affecting Biodegradation

Chemical and Physical Properties of Plastics

The properties of plastics, both chemical and physical, directly influence their biodegradability and mechanism of biodegradation.

Physical properties of plastics that determine their biodegradability include surface conditions like surface area, hydrophilic and hydrophobic properties (Tokiwa et al. 2009) thickness of the material, transmittance of light, especially UV light amongst others. The physical form of the materials such as films, pellets, powder or fibres (Arkatkar et al. 2009) also affects their degradation.

Chemical properties of plastics that influence their biodegradability are first order structures like chemical structure, presence of active functional groups molecular weight and molecular weight distribution, higher order structures like crystal structure, degree of crystallinity, and (Tokiwa et al. 2009; Arkatkar et al. 2009).

Microbial Factors

Microbes like bacteria and fungi can degrade both natural and synthetic plastics in mixed or pure cultures (Shah et al. 2008; Arkatkar et al. 2009). Factors affecting biodegradation rates of plastics include microbial species, moisture content, high temperature (50–65 °C), acidic conditions, nutrient availability as well as the nature and chemical composition of the waste (Kandakatla et al. 2012).

Degradation of different polymers has been evaluated in various studies:

- Bacteria and fungi were found capable of utilizing different plastic materials like polyethylene and polyurethane as sole carbon and/or nitrogen sources (Zheng et al. 2005; Sivan et al. 2006; Nayak and Tiwari 2011)
- Polyethylene was degraded by a bacterial species named *Rhodococcus ruber* during 60 days of incubation (Sivan et al. 2006). The rate of bacterial differentiation was higher for *R. ruber* than for *Pseudomonas* sp. The viability of this strain was tested using the LIVE/DEAD Baclight kit and cells remained alive for the entire 60 days of incubation even though the proportion of dead cells increased over the incubation period.
- Polythene bags and plastic cups were biodegraded by various bacterial and fungal species by incubating with soil from five different locations. Biodegradation was measured in terms of weight loss and polythene was easier to biodegrade compared to higher density plastic cups (Nayak and Tiwari 2011).
- Polyurethane was degraded by *Comamonas Acidovorans TB-35*, *Curvularia senegalensis, Fusarium solani, Aureobasidium pullulans, Cladosporium sp., Pseudomonas chlororaphis* (Zheng et al. 2005).

In the plastics degradation process, plastics can serve as the sole source of carbon and energy in soil and it was found that small fragments were consumed faster than larger ones. However, this was not considered an indication for biodegradation which requires reduction in molecular weight (Sivan et al. 2006) or generation of biomass or CO_2 with plastics as the sole substrate.

2.2.2 Biodegradation Tests

Biodegradation of plastics in the environment can be tested in several ways as listed below:

1. Field tests
2. Simulation tests
3. Laboratory tests

Field Tests Biodegradation of plastic materials can be tested in field tests by burying samples in soil, placing them in a lake or river or performing a full scale composting process. However, environmental conditions cannot be controlled and it is often difficult to be certain that loss of material weight is due to biodegradation only. Simulation tests are applied as an alternative to field tests (Shah et al. 2008).

Simulation Tests Here experiments are conducted in reactors under controlled laboratory conditions. Although simulation test conditions are near environmental conditions, important parameters can be controlled, adjusted and monitored.

Laboratory Tests The most reproducible biodegradation tests are laboratory tests. In these tests, defined culture media are used and inoculated with either a mixed microbial culture or pure cultures of microbes which may have been isolated or acclimated for a particular polymer. In laboratory tests, it is possible to conclusively determine degradation rates of plastics under 'optimal' but not natural conditions. These tests have great value for systematic investigations and deeper understanding of the mechanisms involved.

Standard Testing Methods (Muller 2005)

1. **Visual observations:** Visual observations which include roughening of the surface, formation of holes or cracks, defragmentation or changes in colour, and other images using Scanning Electron Microscopy (SEM) or Atomic Force Microscopy (AFM) can serve as indicative parameters of the biodegradation process. However, these parameters do not conclusively prove biodegradation in terms of the metabolism.
2. **Weight loss measurements** *Determination of residual polymer*: Weight loss measurements to determine loss of polymer due to biodegradation is an easy and relatively inexpensive method. However, it provides no solid proof of degradation unless there is a simultaneous increase in microbial counts.
3. **Changes in mechanical properties and molar mass:** As with visual observations, changes in material properties do not prove biodegradation of the material. Properties such as tensile strength are very sensitive to change in molar mass of polymer and thus can be considered as indicators of biodegradation processes.
4. **Clear-zone formation:** Clear-zone test is a very simple qualitative method that is used to screen organisms that can degrade a certain polymer (Augusta et al. 1993). In this test, the polymer is dispersed as very fine particles within the synthetic agar medium, and results in the agar having an opaque appearance. After inoculation with microbes, the formation of a clear halo around the colony indicates that the organisms are able to depolymerize the polymer which is the first step of biodegradation. However, this method was found to be more effective for screening dissolved compounds like antibiotics (Mohanta and Goel 2014) rather than solid materials like plastic films fragments (Nithin 2013).
5. **Agar Plate tests:** An agar plate test was developed for qualitative screening of biological growth in the presence of plastics (Nithin 2013). Standard petri plates were filled with nutrient agar and two grades of plastic film (cut to a diameter slightly smaller than the diameter of the petri dish) were placed on it. The plastic

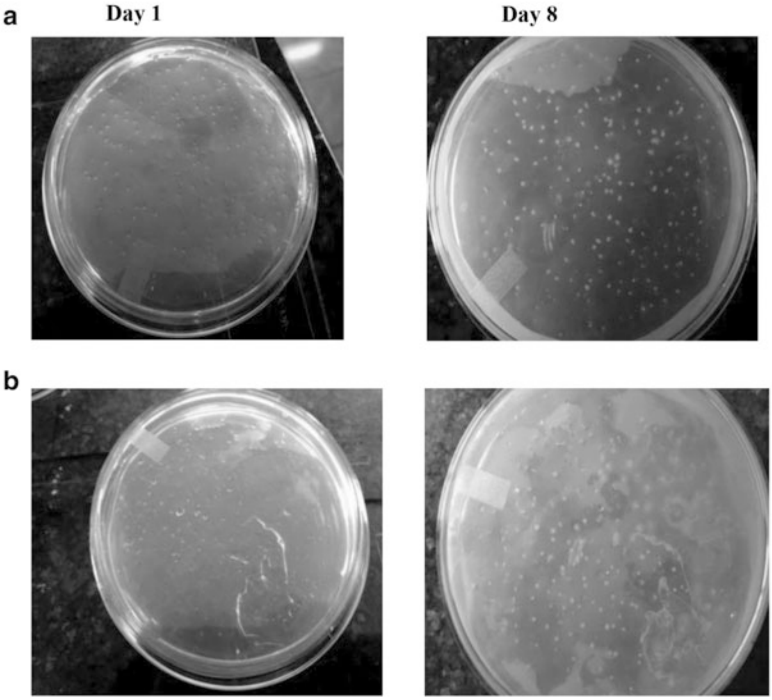


Fig. 11.4 (**a**) (Grade 1) and (**b**) (Grade 2). Agar plates showing biological growth on plastic after incubation for 8 days

film was perforated with a needle as shown in the following photos. After a week of incubation, bacterial colonies were found in both grades of plastic proving that growth was possible on the surface of plastic (Fig. 11.4a, b). Bacterial growth in these experiments was attributed to growth on nutrient media in agar plates and adhesion of colonies to plastic films.

2.2.3 Enhancement of Biodegradation

Efforts were made to enhance the rate of biodegradation of these recalcitrant polymers by modifying the polymer or initiating the degradation process by generating free radicals, etc. (Arkatkar et al. 2009). Methods for enhancing biodegradation of plastics include (Bhardwaj et al. 2013):

1. Isolating and acclimating microorganisms that can degrade these polymers.
2. Improve the attachment of organisms to the recalcitrant polymer surface.
3. Pre-treat the polymeric materials using thermal, UV, microwave, high-energy radiation and chemicals.

4. Mix polymers or plastics with natural biodegradable polymers including cellulose or starch or with biodegradable synthetic polymers like polylactic acid (PLA) or Polycaprolactum (PCL)
5. Mix with pro-oxidants
6. Use genetically-modified microbes for biodegrading these polymers.

3 Summary

The increasing amounts of plastic waste being generated all over the world have become another major environmental issue. Plastics tend to have long lives in the environment and are associated with several problems including disruption of ecosystems, generation of toxic pollutants, creation of aesthetic and civic nuisance conditions, and blocking of drains. These relatively inert materials can be degraded abiotically and/or biotically under favourable environmental conditions. Environmental factors that favour the degradation of plastics include light, heat, acidity, presence of catalysts and free radicals, metal-organo complexes, and acclimated microbial consortia.

References

Arkatkar A., Arutchelvi, J., Sudhakar, M., Bhaduri, S., Parasu, V.U. and Mukesh, D., 2009. Approaches to Enhance the Biodegradation of Polyolefins. *The Open Environmental Engineering Journal*, **2**, 68–80.

Augusta, J., Joachim, R., Miiller, A. and Widdecke, H., 1993. A rapid evaluation plate test for the biodegradability of plastics. *Appl. Microbiol. Biotechnol.*, **39**, 673–678.

Barnes, D.K.A., Galgani, F., Thompson, R.C. and Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. *Phil. Trans. R. Soc. B*, **364**, 1985–1998, doi:10.1098/rstb.2008.0205.

Bhardwaj, H., Gupta, R. and Tiwari, A., 2013. Communities of Microbial Enzymes Associated with Biodegradation of Plastics. *J Polym Environ*, **21**, 575–579, DOI 10.1007/s10924-012-0456-z.

FICCI, 2014. Potential of plastics industry in Northern India with special focus on plasticulture and food processing – 2014. A report on plastic industry. Retrieved from http://ficci.in/spdocument/20396/Knowledge-Paper-ps.pdf on 3 Sep 2016.

Kandakatla, P., Mahto, B. and Goel, S., 2012. Extent and rate of biodegradation of different organic components in municipal solid waste. *International Journal of Environment and Waste Management*, **11(4)**, 350–365.

Masayuki, S., 2001. Biodegradation of plastics. *Current Opinion in Biotechnology*, **12**, 242–247.

Mohanta, T. and Goel, S., 2014. Prevalence of antibiotic resistant bacteria in three different aquatic environments over three seasons. *Environmental Monitoring and Assessment*, **186**, 5089–5100.

Muller, R., 2005. Biodegradability of Polymers: Regulations and Methods for Testing: General Aspects and Special Applications. Wiley Publishers, DOI:10.1002/3527600035.bpola012.

Mutha, N.H., Patel, M. and Premnath, V., 2006. Plastics materials flow analysis for India. *Resources, Conservation and Recycling*, **47**, 222–244.

Nayak, P. and Tiwari, A., 2011. Biodegradability of Polythene and Plastic by the Help of Microorganism: A Way for Brighter Future. *J Environment Analytic Toxicol*, **1**, 111.

Nithin, B., 2013. Biodegradation of Plastics. *M. Tech. thesis,* IIT Kharagpur.

Roy, P.K., Hakkarainen, M., Varma, I.K. and Albertsson, A.-C., 2011. Degradable Polyethylene: Fantasy or Reality. *Environ. Sci. Technol*., **45**, 4217–4227.

Seymour, R.B., 1989. Polymer Science Before and After 1899: Notable developments during the lifetime of Maurtis Dekker. *J. Macromol. Sci. Chem*., **26**, 1023–1032.

Shah, A.A., Hasan, F., Hameed, A. and Ahmed, S., 2008. Biological degradation of plastics: A comprehensive review. *Biotechnology Advances*, **26**, 246–265.

Singh, B. and Sharma, N., 2008. Mechanistic implications of plastic degradation. *Polymer Degradation and Stability*, **93**, 561–584.

Sivan, A., Szanto, M. and Pavlov, V., 2006. Biofilm development of the polyethylene-degrading bacterium *Rhodococcus ruber*. *Appl. Microbiol. Biotechnol*., **72(2)**, 346–352.

Sivan, Alex, 2011. New perspectives in plastic biodegradation. *Current Opinion in Biotechnology*, **22**, 422–426.

Teuten, E.L., Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Bjorn, A., Rowland, S.J., Thompson, R.C., Galloway, T.S., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Viet, P. H., Tana, T.S., Prudente, M., Boonyatumanond, R., Zakaria, M.P., Akkhavong, K., Ogata, Y., Hirai, H., Iwasa, S., Mizukawa, K., Hagina, Y., Imamura, A., Saha, M. and Takada, H., 2009. Transport and release of chemicals from plastics to the environment and to wildlife. *Phil. Trans. R. Soc. B*, **364**, 2027–2045, doi:10.1098/rstb.2008.0284.

Tokiwa, Y., Calabia, B.P., Ugwu, C.U. and Aiba, S., 2009. Biodegradability of Plastics. *International Journal of Molecular Sciences*, **10(9)**, 3722–3742.

US Environmental Protection Agency (USEPA). http://www.epa.gov/osw/conserve/materials/plastics.htm, downloaded 2012.

Zheng, Y., Yanful, E.K. and Bassi, A.S., 2005. A review of plastic waste biodegradation. *Crit. Rev. Biotechnol*., **25**, 243–250.

Chapter 12
Electronic Waste (E-Waste) Generation and Management

Deblina Dutta and Sudha Goel

1 Introduction

With the beginning of this millennium, the world has been struggling to deal with increasing quantities of solid waste. Rapid advancement in technology, especially the production of electrical and electronic goods has resulted in a new stream of waste known as electrical and electronic waste making it the fastest growing waste stream in the world. Equipment at the end-of-life (EOL) leads to e-waste generation in huge amounts. Increasing obsolescence rates of electrical and electronic equipment result in higher e-waste generation rates leading to disposal problems. E-waste, if managed improperly or inadequately, can cause enormous impact on the global environment as well as on human health.

Discarded electronic devices like televisions, PCs, floppies, CDs, batteries, switches, telephones, air conditioners, cell phones, electronic toys, refrigerators, washing machines, kitchen ware and even parts of aircraft are included in the list of electrical and electronic wastes and the substances present in them are listed in Table 12.1. Typical weights and life-spans of some of the most common electronic waste items are summarised in Table 12.2. E-waste covers more than 1000 materials which can be categorized as 'hazardous' or 'non-hazardous'. Mostly, it consists of ferrous and non-ferrous metals, plastics, glass, plywood, printed circuit

---

D. Dutta (✉)
School of Environmental Science and Engineering, Indian Institute of Technology Kharagpur, Kharagpur 721302, India
e-mail: deblina69envs@gmail.com

S. Goel
Civil Engineering Department, Indian Institute of Technology Kharagpur,
Kharagpur 721302, WB, India

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_12

Table 12.1 Substances present in e-waste

Component	Possible substances present
Plastic	Phthalate plasticizer, Brominated flame retardant (BFR)
Insulation	Asbestos, refractory ceramic fibre
Cathode ray tube (CRT)	Lead, antimony, mercury, phosphorus
Liquid-crystal display	Mercury
Rubber	Phthalate plasticizer, BFR
Wiring/Electrical	Phthalate plasticizer, lead, BFR
Circuit board	Lead, beryllium, antimony, BFR
Thermostat	Mercury
BFR – containing plastic BFRs	BFR
Batteries	Lead, lithium, cadmium, mercury
External electric cables	BFRs, plasticizers
Electrolyte capacitors	Glycol, other unknown substances

Source: Jadhav (2013)

Table 12.2 Typical weights and life spans of e-wastes

Item	Mass (kg)	Typical life span (years)
Computer	25	3
Television	30	5
Mobile telephone	0.1	2
Video recorder and DVD player	5	5
Radio	2	10
Photocopier	60	8
Telephone	1	5
Refrigerator	35	10
Air conditioning unit	55	12
Electric heaters	5	20
Washing machine	65	8
Electric cooker	60	10
Iron	1	10
Food mixer	1	5
Microwave	15	7
Hair dryer	1	10
Vacuum cleaner	10	10
Toaster	1	5

Source: Premalatha et al. (2014)

boards, rubber, concrete and ceramics, etc. Iron and steel constitute a major part of Waste Electrical and Electronic Equipment (WEEE). Non-ferrous metals include copper, aluminium, precious metals like gold, silver, platinum, palladium, etc. Heavy metals like lead, mercury, arsenic, cadmium, etc. are also present in large quantities.

1.1 Problems Associated with E-Waste

Proper care, management and handling procedures should be taken into account when dealing with e-waste. Improper handling may cause serious damage to human health as well as to the environment. Table 12.3 shows some of the constituents present in e-waste and their effects on human health and on the environment.

2 E-Waste Generation

2.1 Global Perspective of E-Waste Generation

In a United Nations University-Institute for the Advanced Study of Sustainability (UNU-IAS) report published in 2015, global generation of e-waste was estimated to be 41.8 million tons per year (Baldé et al. 2015). Asia was found to be the largest producer of e-waste with a generation rate of 16 million tons per year which amounts to a per capita generation rate of 3.7 kg/person-year. In comparison, Europe had the highest per capita generation rate of 15.6 kg/person-year. A list of the top ten e-waste generating countries in order of the annual e-waste generated is provided in Table 12.4 based on the UNU-IAS report. India is the fifth largest generator of e-waste at the global level and third in Asia behind China and Japan. However, per capita e-waste generation rates in India are amongst the lowest (1.3 kg/capita-y) in comparison to the highest per capita e-waste generation rates of 28.3 kg/capita-y in Norway (a complete list of all countries ranked in order of per capita e-waste generation rates is provided in Appendix C, based on the UNU-IAS report, 2015).

Major generators of e-waste are developed countries such as the USA, several European nations and Brazil. They produce large amounts of e-waste each year and in the name of international trade, many developed countries are dumping their e-waste in developing countries like India and China. Developed countries mainly adopt the "reuse" procedure to save their environment and money flow.

In the global scenario, the demand for certain metals like rare earth metals, platinum group elements, certain base metals and precious metals, etc. has increased day-by-day but the supply has become negative. So to maintain the demand and supply ratio of the requisite metals, various technologies are used. This process is also known as 'Urban mining'. Urban mining is the process of recovering different compounds and elements from various products and wastes which would otherwise be left open in the environment to cause different levels of pollution (Fig. 12.1). By changing our way of thinking, we can reuse and recycle valuable components from the wastes, paving the way towards a zero-landfill future and can also save our environment.

Table 12.3 Effects of e-waste on human health and environment

E-waste	Constituent	Effect on human health	Effect on environment	References
Solder in printed circuit boards, glass panels and gaskets in computer monitors, CRT screens, batteries	Lead (Pb)	Damages central and peripheral nervous systems, kidney and affects brain development of children	Bioaccumulation, disrupts photosynthesis	Ramachandra and Saira Varghese (2004)
Chip resistors and semiconductors, rechargeable Ni-Cd batteries, fluorescent layer (CRT screens), printer inks and toners	Cadmium (Cd)	Irreversible toxic effects on human neural health, accumulates in kidney and liver, teratogenic	Bioaccumulation in the aquatic as well as terrestrial environment	Ramachandra and Saira Varghese (2004)
Relays and switches, printed circuit boards, fluorescent lamps and some batteries	Mercury (Hg)	Chronic damage to the brain, respiratory systems and skin disorders	Bioaccumulation in fishes	Ramachandra and Saira Varghese (2004)
Corrosion protection of untreated and galvanized steel plates, decorator or hardener for steel housings	Hexavalent chromium VI (Cr)	Asthmatic bronchitis, DNA damage, allergic reactions	Leads to air and water pollution	Ramachandra and Saira Varghese (2004)
Cabling and computer housing	Plastics	Incineration generates dioxins.It causes reproductive problems, immune system damage, and interferes with hormones	Non-degradable so can affect the environment in every respect	Ramachandra and Saira Varghese (2004)
Plastic casing of electronic equipment and circuit boards	Brominated Flame Retardants (BFR)	Disrupts endocrine system functions	Persistent in the environment	Ramachandra and Saira Varghese (2004)
Front panel of CRTs	Barium (Ba)	Muscle weakness, damages heart and liver	May result in explosive gases (hydrogen) if wetted	Ramachandra and Saira Varghese (2004) and Begum (2013)
Motherboard, power supply boxes which contain silicon controlled rectifiers, beamline components	Beryllium (Be)	Carcinogenic causes chronic beryllicosis, skin diseases likewarts		Begum (2013)

Condensers, transformers	PCB (polychlorinated biphenyls)	Causes cancer, affects the immune system, reproductive system, nervous and endocrine system	Persistent and bioaccumulation	Begum (2013)
Fire retardants for plastics. TBBA is widely used as flame retardant in printed wiring boards and covers for components	TBBA (tetrabromo- bisphenol-A) • PBB (polybrominated biphenyls) • PBDE (polybrominated diphenyl ethers)	Causes long-term problems health and is more poisonous when burned		Begum (2013)
Cooling unit, insulation foam	Chlorofluorocarbons (CFC)	Combustion results in toxic emissions		Begum (2013)
Light emitting diodes (LEDs)	Arsenic (As) in the form of gallium arsenide	Acutely poisonous and injurious to health		Begum (2013)
Li-batteries	Lithium (Li)		May produce explosive gases (hydrogen) if wetted	Begum (2013)
Rechargeable Ni-Cd batteries or NiMH batteries, electron gun in CRT	Nickel (Ni)	May cause allergic reactions		Begum (2013)
Fluorescent layer in CRT- screen	Rare earth elements (Yttrium, Europium, Neodymium, etc.)	Irritates skin and eyes		Begum (2013)
CRT screen	Zinc sulphide	Toxic when inhaled		Begum (2013)
Condensers, liquid crystal display	Toxic organic substances			Begum (2013)
Toner cartridges for laser printers/ copiers	Toner dust	Health risk when dust is inhaled		Begum (2013)

Source: Report on Assessment of Electronic Wastes in Mumbai-Pune Area – MPCB, March, 2007

Table 12.4 Top ten e-waste generating countries in terms of kilotons/year

Rank	Country	Continent	Kg/person-year	Kilo tons/year	Regulations[a]	Population (in 1000s)
1	USA	Americas	22.1	7072	no	3,19,701
2	China	Asia	4.4	6033	yes	13,67,520
3	Japan	Asia	17.3	2200	yes	1,27,061
4	Germany	Europe	21.6	1769	yes	81,589
5	India	Asia	1.3	1641	no	12,55,565
6	UK andN Ireland	Europe	23.5	1511	yes	64,271
7	France	Europe	22.1	1419	yes	63,996
8	Brazil	Americas	7	1412	no	2,01,413
9	Russia	Europe	8.7	1231	no	1,40,955
10	Italy	Europe	17.6	1077	yes	61,156

Source: Baldé et al. (2015)

[a] National regulations in effect, 2013

Fig. 12.1 Management of e-waste through urban mining (http://ecyclingusa.com)

Table 12.5 E-waste/WEEE generation in ten states of India

Rank	States	WEEE (tons)	Percentage (%)
1	Maharashtra	20,270.59	18.49
2	Tamil Nadu	13,486.24	12.30
3	Andhra Pradesh	12,780.33	11.66
4	Uttar Pradesh	10,381.11	9.47
5	West Bengal	10,059.36	9.18
6	Delhi	9729.15	8.87
7	Karnataka	9118.74	8.32
8	Gujarat	8994.33	8.20
9	Madhya Pradesh	7800.62	7.11
10	Punjab	6958.46	6.35
Total		**109,578.93**	**100**

Source: Vats and Singh (2014)

2.2 *Indian Scenario of E-Waste Generation and Management*

The most recent estimate (2013) of e-waste generation in India is 1.6 million tons/y (Baldé et al. 2015). The top ten states in India generating e-waste are shown in Table 12.5. These 10 states generate 70% of the total e-waste and 65 cities are responsible for generating 60% of the total e-waste in the country (Vats and Singh 2014). E-waste generation in India is estimated to be increasing by 10% annually. Issues regarding collection of information from industry and compliance with regulations are major deterrents in e-waste management in India.

In response to the E-waste (Management and Handling) Rules, 2015, CPCB now has 138 registered e-waste recyclers as of Nov 2014 with a total handling capacity of 0.35 million tons/annum.

3 Management Practices for E-Waste

For the proper management of e-waste, effective and practical solutions are required. First of all, generation of waste from source has to be reduced. Second, collection centres should be located where transportation is available. After collection, wastes should be safely transferred to different recycling centres for further processing. Various rules, regulations and methods are adopted for the management of e-waste (Fig. 12.2). A comprehensive review of e-waste management issues is available in Terazono et al. (2006).

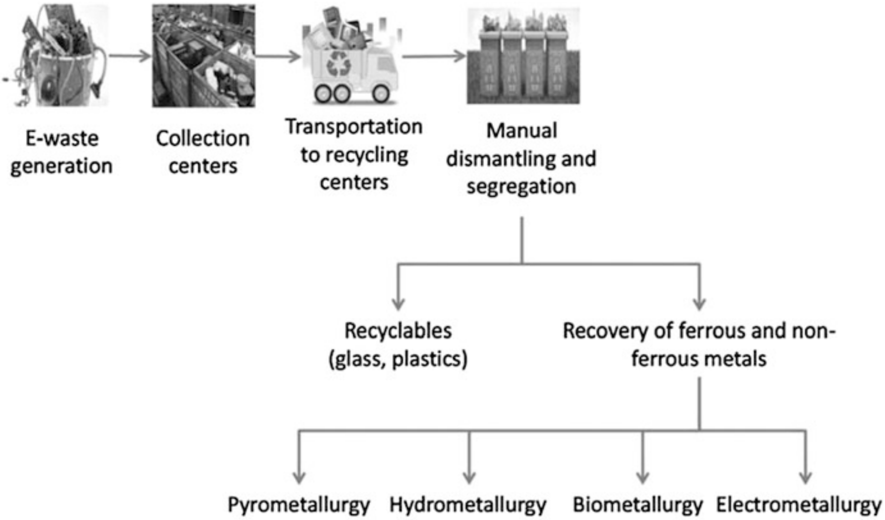


Fig. 12.2 Steps involved in E-waste management

3.1 E-Waste (Management and Handling) Rules

The E-waste (Management and Handling) Rules, 2011 have been modified in the year 2015 and apply to every manufacturer, producer, consumer, bulk consumer, collection centres, dealers, refurbishers, dismantlers and recyclers involved in the manufacture, sale, transfer, purchase, collection, storage and processing of e-waste or electrical and electronic equipment (EEE). It also explains the role of the producer clearly**.** Producer Responsibility Organizations (PROs) are also included in the new rules of 2015 in addition to the Extended Producer Responsibility (EPR).

Penalty and punishment for non-compliance are defined in Sections 15 and 16 of the Environment (Protection) Act, 1986 which says that whoever fails to comply with the rules will be punishable with imprisonment for a certain period which may be extended to 5 years or with penalty which may extend to Rs 1 lakh. More details regarding these rules can be found in Appendix B of this book and the full text of the rules is available at the Ministry of Environment and Forests (MoEF) website (http://www.moef.gov.in/).

3.2 Extended Producer Responsibility (EPR)

EPR is an environment protection strategy which makes the producer responsible for the entire life-cycle of the product and principally for take-back, recycling and final disposal. EPR uses financial incentives to encourage manufacturers to design environmentally-friendly products and hold them responsible for the costs of managing their products to the end-of-life (EOL). A summary of EPR legislation in different countries is provided in Table 12.6.

3.3 Take-Back Policy

Several countries have policies related to return of appliances to their manufacturers, also called ‘take-back’ policies. Europe has a WEEE directive which requires manufacturers to take-back their products. Asian countries like China, Japan, and Korea have policies that require recycling of discarded appliances. Special national funding is available in China for doing so while manufacturers in Japan are allowed to charge consumer fees for return of appliances. Manufacturers are required to pay recyclers a fee in Korea (Terazono et al. 2006).

Considering the take-back policy in India, most manufacturers of electrical and electronic appliances like Apple, Microsoft, Panasonic, PCS, Philips, Sharp, Sony, Sony Ericsson and Toshiba provide a take-back option. Samsung has a take-back service but only one collection centre for all of India; HCL and WIPRO have the best take-back policies in India. Other brands like Nokia, Acer, Motorola and LGE perform comparatively well. There is also a discount process where old products can be exchanged for new ones at a discounted price. However, these policies apply only to some electrical and electronic companies and needs to be adopted by developed and under-developed countries for managing e-waste.

3.4 Collection Centres and Deposit Boxes

Some electronic companies like HP, Nokia and Microsoft operating in India in various towns and cities have deposit boxes in their stores for the collection of end-of-life products for recycling purposes. There are certain collection centres in different parts of the states which collect e-waste and transport them to different recycling units for further processing.

3.5 Basel Convention

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, generally shortened to “Basel Convention” is an international treaty that was designed to reduce the movement of hazardous waste between nations, and particularly to prevent transport of hazardous waste from developed to developing countries. The twelfth meeting of the Conference of Parties (COPs) to the Basel Convention was held from 4 to 15 May 2015 in Geneva and

Table 12.6 The role of EPR and e-waste legislation in different countries

Countries	EPR concept
European Union	The directive mainly focuses on reuse, recycle and recovery of e-wastes and dismantling of electronic parts and recycling of materials, proper collection systems to reduce disposal and incorporate best management practices.
Switzerland	This country was the first to develop and implement methods for collection, transportation, recycling/treatment and disposal of e-waste. Three producer responsibility organizations (PROs): The Swiss Association for Information Communication and Organizational Technology (SWICO); the Stiftung Entsorgung Schweiz (SENS); and Swiss Lighting Recycling Foundation (SLRS) oversee these systems based on the concept of EPR.
The United States of America	Established funding for the collection and recycling of e-waste. Consumers pay a fee called Advance Recycling Fee (ARF) at the time of purchase that goes to the state and is used to reimburse recyclers and collectors.
Japan	Manufacturers and importers are responsible for taking back end-of-life electronics for recycling and waste management. Consumers pay a fee that is directly used to meet the expenses of recycling and transportation.
South Korea	Local manufacturers, distributors and importers of e-goods are required to achieve official recycling targets. Government keeps an account for depositing funds for recycling, which are refundable depending on the amount of waste recycled.
Australia	Importers, manufacturers and distributors have to subscribe to mandatory, co-regulatory, or voluntary schemes for managing the disposal of computers and televisions.
Singapore	Export, import or transit waste requires a permit from the Pollution Control Department (PCD) of Singapore. If documents are available to support that the products are in good condition and can be reused, only then permission is granted.
China	(a) Pollution prevention and controls on the use, dismantling and disposal of e-waste, under "Technical Policies for Controlling Pollution of WEEE, 2006", (b) Certificate is required for e-waste recycling systems, under "Administrative Measures for the Prevention and Control of Environmental Pollution by WEEE, 2008", and (c) All producers and importers responsible for their products, collection and treatment funds, under "Regulation on the Administration of the Recovery and Disposal of WEEE, 2011".
India	According to MoEF, 2011, producers are responsible for collection of e-waste generated after the end-of-life of the e-products. The legislation has been modified in 2015 with new responsibilities for the producers as well as consumers.
African countries	The use of e-goods is very less in the African countries. No specific e-waste legislation has been implemented in those countries.

Source: Premalatha et al. (2014)

included the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade and the Stockholm Convention on Persistent Organic Pollutants, respectively. One of the major outcomes of this meeting was the formulation of technical guidelines regarding the transboundary movement of e-waste which is a matter of growing concern for less developed countries. This meeting also deliberated over the definition of ‘waste’ and ‘non-waste’ since waste in one country is a usable second-hand appliance in another country. The need for inventorizing the amount of e-waste generated in different countries was also highlighted (UNEP 2015).

Major issues that were pointed out in this meeting were:

(a) Residual lifespan and age of used equipment;
(b) Management of hazardous wastes from repairing and refurbishment operations in developing countries;
(c) Obsolete technologies like cathode ray tubes; and
(d) Existence of hazardous components in used equipments.

4 Techniques for Recycling and Recovery

The most useful techniques for management of electronic wastes are recycling and recovery.

Recycle The first level of environmentally sound e-waste treatment includes decontamination, dismantling and segregation. After dismantling, the parts which can be recycled are transported to the respective industries for further use and the remaining parts are used for recovery of metals. Each of the electronic products consists of glass, plastics, ferrous and non-ferrous metals. Plastics constitute about 20.6% of the product (ETC/RWM 2003). Iron and steel comprise the largest fraction in WEEE materials, 47.9%. The non-ferrous component contributed 12.7% of which Cu weighed 7% (Bandyopadhyay 2008). After dismantling electronic products, segregation of the different parts is done and these are recycled and processed accordingly. The idea of developing economic and environmental benefits through inter-firm waste exchange is known as ‘Industrial Symbiosis’ in which one firm’s waste becomes the raw material of another firm.

Currently in India, there are two segments managing the recycling and disposal of the electronic wastes namely: formal recyclers and informal recyclers. Formal recyclers deal with a very small percentage which is close to 5% of the total e-waste recycled in India (19,000 MT) whereas the rest is recycled by informal recyclers. Formal recyclers are less in number and follow environmental, health and safety rules as they are frequently audited and certified by renowned regulatory agencies. Informal recyclers are more in number, better networked and more skilled in collection and recycling of e-waste.

4.1 Glass

Glass in electronic products can be recycled and used for different applications. Cathode Ray Tube (CRT) glass in old computer monitors and televisions are used as raw materials for ceramic glazes (Andreola et al. 2005). CRTs contain hazardous materials like lead, so they should be handled properly and recycled before reuse or disposal. LCD screens in television sets contain several thin mercury lamps and liquid crystals which makes them a challenge for recycling.

4.2 Plastic

All plastics are transferred to recyclers who use them as raw material to manufacture new products without altering their properties. However, there is a big challenge in separating the high value plastic streams from the mixed plastics present in electronic waste. CreaSolv process has been developed for the recovery of polymer fraction from the plastics present in mobile phones (Maurer et al. 2004). Plastic recovery techniques are difficult due to the variety of polymers used in e-goods and the labour-intensive nature of separation of plastic from e-waste.

4.3 Ferrous Metals and Non-ferrous Metals

Magnetic separation of ferrous metals and non-ferrous metals can be done to separate the two fractions. Recovery of various non-ferrous metals can be done by using any of the following processes:

1. Pyrometallurgy
2. Hydrometallurgy
3. Biometallurgy or Bioleaching
4. Electrometallurgy

4.3.1 Pyrometallurgy

Pyrometallurgy is the thermal treatment of minerals and metallurgical ores resulting in the physical and chemical transformation of valuable metals. In this process, electronic waste is heated above 1500 °C in a closed reactor, i.e. in the absence of oxygen, especially designed to ensure zero emissions. This process includes a number of procedures like calcining, roasting, smelting and refining. Elements that can be recovered by pyrometallurgical process include oxides of less reactive elements like iron, zinc, copper, manganese, chromium, tin, etc. Some pyrometallurgical studies for metal recovery are summarized in Table 12.7.

4.3.2 Hydrometallurgy

Appropriate chemical reagents are used in hydrometallurgy to dissolve metals from e-waste. The various chemical reagents used are aqueous and organic solvents, mineral acids, some bases, and mixed acids. The various types of solvents used are cyanides, thiourea, and thiosulfate, for the recovery of precious metals from e-waste. The different processes involved in hydro-metallurgy are:

Table 12.7 Pyrometallurgical methods for recovery of metals from electronic waste

Techniques	Metals recovered	Main results	References
Noranda process, Quebec, Canada	Cu, Au, Ag, Pt, Pd, Se, Te, Ni	Recovery of base metal like copper and precious metals.	Veldbuizen and Sippel (1994)
Boliden Rönnskår Smelter, Sweden	Cu, Ag, Au, Pd, Ni, Se, Zn, Pb	Recovery of copper and precious metals.	Cui and Zhang (2008)
Test at Rönnskår Smelter, Sweden	Copper and precious metals	Recovery of copper and precious metals in the zinc fuming process.	APME (2000)
Umicore's precious metal refining process, Hoboken, Belgium	Base metals, precious metals, platinum group metals and selenium, tellurium, indium	Almost complete recovery of base metals, precious metals and special metals such as Sb, Bi, Sn, Se, Te, In.	Hageluken (2006)
Full scale trial at Umicore's smelter	All metals present in the electronic scrap	Metal recovery was not affected by the presence of 6% plastics in e-waste.	Brusselaers et al. (2005)
Dunn's patent for gold refining	Gold	Gold with 99.9% purity was recovered from gold scraps.	Dunn et al. (1991)
Day's patent for refractory ceramic precious metals scraps	Precious metals such as platinum and palladium	Recovery of platinum and palladium of about 80.3% and 94.2%, respectively.	Day (1984)
Aleksandrovich's patent for recovery of gold and platinum group metals from electronic scraps	PGM and gold	PGM and gold were recovered.	Aleksandrovich et al. (1998)
Thermal treatment	Phosphate and rare earth metals (REMs) from Korean monazite ore	>90% REMs	Kumari et al. (2015)

Source: Cui and Zhang (2008)

Table 12.8 Hydrometallurgical methods for recovery of metals from electronic waste

Materials	Metals recovered	Efficiency	References
Computer chips	Au	Gold flakes	Sheng and Etsell (2007)
Ceramic capacitors	Ni	Ni in solution	Kim et al. (2007)
E-waste	Au, Pd, Pt, Ag	Au – 98%; Pd – 96%; Pt – 92%; Ag – 84%	Kogan (2006)
E-waste	Au, Ag, Pd	92% for Au, Ag, Pd	Zhou et al. (2005)
E-waste	Cu, Pb, Sn	Cu, Pb, Sn	Mecucci and Scott (2002)
E-waste	Au, Ni	Au, Ni	Zakrewski et al. (1992)
Solder of waste printed circuit boards	Lead	Pb – 99.99%	Kumari et al. (2010)
Printed circuit boards	Cu, Fe, Ni, Pb	Cu, Fe, Ni – 99.99% Pb – 36.7%	Jha et al. (2010)

(a) Leaching: The most efficient leaching agents are acids as they have the capacity to solubilise both, base and precious metals.
(b) Solution concentration and purification: The main purpose is to remove undesired impurities so that metal concentration in solution increases. Purification of the solution is done by ion exchange, adsorption and solvent extraction processes.
(c) Recovery of metal: After solution purification, metal is to be recovered chemically or electrochemically.

Applications of hydrometallurgical methods for metals recovery from e-waste are summarized in Table 12.8.

4.3.3 Biometallurgy

Biometallurgy involves the use of microbes in an aqueous environment to produce metals and has been used for decades for the recovery of metals like copper, gold and uranium. Almost a quarter of the global production of copper is done by bioleaching (Madigan et al. 2015). Bioleaching is defined as the mobilization of metal cations from mineral ores by biological oxidation. Biometallurgical methods used for metal recovery are summarized in Table 12.9.

4.3.4 Electrometallurgy

Electrometallurgy involves the use of electro-plating or electro-deposition methods. In these methods, electrolytic cells with different types of electrolytes and electrodes are used for deposition of expensive metals on the surface of the appropriate

Table 12.9 Biometallurgical methods for metal recovery from electronic waste

Materials	Metals recovered %		Microorganism used	References
	Nickel	Cadmium		
Ni-Cd battery	96.50	100	*A. ferrooxidans*	Cerruti et al. (1998)
	66.10	100	Indigenous acidophilic thiobacilli in sewage sludge	Zhu et al. (2003)
	–	84	*A. ferrooxidans* and *A. thiooxidans*	Velgosova et al. (2010)
Electronic scrap	Cu, Sn, Ni, Pb, Zn, Al		*A. ferrooxidans, A. thiooxidans, A. niger* and *P. simplicissimum*	Brandl et al. (2001)
Electronic waste	Cu, Zn, Al, Ni		*Thermosulfidooxidans sulfobacilllus* + *Thermoplasma acidophilum*	Ilyas et al. (2010)
Electronic waste	Cu, Pb, Zn		*A. ferrooxidans, A. thiooxidans* and mixture	Wang et al. (2009)
Electronic waste	Cu		*A. ferrooxidans* and *A. thiooxidans*	Mražíková et al. (2013)

Source: Willner et al. (2015) and Natarajan et al. (2015)

Table 12.10 Electrometallurgical methods for recovery of metals from electronic waste

Materials	Metals recovered	Efficiency	References
Printed circuit boards	Cu	12%	Kumar et al. (2013)
Printed circuit boards	Cu	98%	Masavetas et al. (2009)
Electronic waste	Au, Ag, Cu, Cd, Zn, Ni, Pb, Sn	–	Wiaux (1990)

electrode. Methods and efficiency of metal recovery from e-waste are summarized in Table 12.10. The most common processes used in electrometallurgy are:

(a) Electro-winning: A leach solution containing the metal of interest is added to an electrolytic cell. When current is passed through the cell, the metal is deposited on the cathode while the anode remains inert.
(b) Electro-refining: An acidic electrolyte is added to an electrolytic cell with anode made of impure metal. When current is passed through the cell, the anode dissolves into the electrolyte from where pure metal is deposited on the cathode resulting in greater metal purity.
(c) Electro-forming: Thin metal parts are moulded on pre-formed cathodes and manufactured through electroplating.

5 Conclusions

E-waste management has become a serious concern for the world after municipal solid waste and hazardous waste. Best methods from different countries can be incorporated to develop and design safe and hazard-free e-waste management systems. Proper e-waste management will help in efficient resource recovery and in e-waste management from cradle-to-grave. In India, E-waste (Management and Handling) Rules, 2011 have been modified to E-waste (Management) Rules, 2015, in which producers, distributors, and importers are held responsible for the proper recycling and disposal of e-waste. Efficient collection of e-waste and its treatment can lead to a better environment and huge piles of e-waste can be turned into lucrative products and business opportunities.

References

Aleksandrovich, S., Nicolaevich, E. and Ivanovich, E., 1998. Method of processing of products based on chalcogenides of base metals containing metals of platinum group and gold. Russian Patent, RU2112064, C22B 11/02.

Andreola, F., Barbieri, L., Corradi, A. and Lancellotti, I., 2005. Cathode ray tube glass recycling: An example of clean technology. *Waste Management & Research*, **23**, 314–321.

APME, 2000. Plastics recovery from waste electrical & electronic equipment in non-ferrous metal processes, 8036/GB/07/00. APME (Association of Plastics Manufacturers in Europe) Report.

Baldé, C.P., Wang, F., Kuehr, R. and Huisman, J., 2015. The Global E-Waste Monitor 2014. Bonn, Germany.

Bandyopadhyay, A., 2008. A regulatory approach for e-waste management: A cross- national review of current practice and policy with an assessment and policy recommendation for the Indian perspective. *International Journal of Environment and Waste Management*, **2(1/2)** 139–186.

Begum, K.J., 2013. Electronic Waste (E-Waste) Management in India: A Review. *IOSR Journal of Humanities and Social Science (IOSR-JHSS)*, **10(4)**, 46–57.

Brandl, H., Bosshard, R. and Wegmann, M., 2001. Computer-munching microbes: Metal leaching from electronic scrap by bacteria and fungi. *Hydrometallurgy*, **59**, 319–326.

Brusselaers, J., Hageluken, C. and Mark, F., 2005. An Eco-efficient Solution for Plastics-Metals-Mixtures from Electronic Waste: the Integrated Metals Smelter. *In:* 5th IDENTIPLAST 2005, the Biennial Conference on the Recycling and Recovery of Plastics Identifying the Opportunities for Plastics Recovery, Brussels, Belgium.

Cerruti, C., Curutchet, G. and Donati, E., 1998. Bio-dissolution of spent nickel-cadmium batteries using *Thiobacillus ferrooxidans*. *Journal of Biotechnology*. **62**, 209–219.

Cui, J. and Zhang, L., 2008. Metallurgical recovery of metals from electronic waste: A review. *Journal of Hazardous Materials*, **158**, 228–256.

Day, F.G., 1984. Recovery of platinum group metals, gold and silver from scrap. US Patent, US4427442.

Dunn, J., Wendell, E. and Carda, D.D., 1991. Chlorination process for recovering gold values from gold alloys. US Patent, US5004500.

ETC/RWM, 2003. European Topic Centre on Resource and Waste Management (Topic Centre of the European Environment Agency) part of the European Environment Information and Observation Network (EIONET). Accessed on January 2007, httkp://waste.eionet.eu.intk/waste/6.

Hageluken, C., 2006. Recycling of electronic scrap at Umicore's integrated metals smelter and refinery. *World of Metallurgy – ERZMETALL*, **59(3)**, 152–161.

Ilyas, S., Ruan, C., Bhatti, H.N., Ghauri, M.A. and Anwar, M.A., 2010. Column bioleaching of metals from electronic scrap. *Hydrometallurgy*, **101**, 135.

Jadhav, S., 2013. Electronic waste: A growing concern in today's environment sustainability. *International Journal of Social Science & Interdisciplinary Research*, **2(2)**, 139–147.

Jha, M.K., Kumar, S.V., Pandey, B.D., Kumar, R. and Lee, J., 2010. Leaching studies for the recovery of metals from the waste Printed Circuit Boards (PCBs). *The Minerals, Metals & Materials Society*, Proceedings of TMS-2010, 945–952.

Kim, E., Lee, J. and Kim, B.S., 2007. Leaching behavior of nickel from waste multi-layer ceramic capacitors. *Hydrometallurgy*, **86**, 89–95.

Kogan, V., 2006. Process for the recovery of precious metals from electronic scrap by hydrometallurgical technique. International Patent, WO/2006/013568 (C22B 11/00), W.I.P. Organization.

Kumar, S.P., Govindaradjane, S. and Sundararajan, T., 2013. Recovery of Copper from Printed Circuit Boards through Electrolytic Process – A Case Study. *International Journal of Engineering Research and Applications (IJERA)*, **3(2)**, 469–473.

Kumari, A., Jha, M.K., Kumar, V., Jeong, J. and Lee, J., 2010. Recovery of lead from the solder of waste Printed Circuit Boards. Proceedings of the XI International Seminar on Mineral Processing Technology (MPT-2010).

Kumari, A., Panda, R., Jha, M.K., Lee, J.Y., Kumar, J.R. and Kumar, V., 2015. Thermal treatment for the separation of phosphate and recovery of rare earth metals (REMs) from Korean monazite. *Journal of Industrial and Engineering Chemistry*, **21**, 696–703.

Madigan, M. T., Martinko, J. M., Bender, K., Buckley, D., and Stahl, D., 2015. *Brock Biology of Microorganisms*. Pearson Publishers.

Masavetas, I., Moutsatsou, A., Nikolaou, E., Spanou, S., Zoikis-Karathanasis, A., Pavlatou, E.A. and Spyrellis, N., 2009. Production of copper powder from printed circuit boards by electrodeposition. *Global NEST Journal*, **11(2)**, 241–247.

Maurer, A., Schlummer, M. and Altnau, G., 2004. Material recovery from mobile phones by CreaSolv process. *In:* Electronic Goes Green. Fraunhofer IZM, Berlin.

Mecucci, A. and Scott, K., 2002. Leaching and electrochemical recovery of copper, lead and tin from scrap printed circuit boards. *Journal of Chemical Technology and Biotechnology*, **77(4)**, 449–457.

Mražíková, A., Marcinčáková, R., Kaduková, J. and Velgosová, O., 2013. Influence of bacterial culture to copper bioleaching from printed circuit boards. *Journal of the Polish Mineral Engineering Society*, July-Dec, 2013, 59–62.

Natarajan, G., Ramanathan, T., Bharadwaj, A. and Ting, Yen-Peng, 2015. Bioleaching of Metals from Major Hazardous Solid Wastes. *In:* Microbiology for Minerals, Metals, Materials and the Environment. Abhilash, B.D., Pandey, and K.A. Natarajan (eds). CRC Press.

Premalatha, M., Abbasi, T., Abbasi, T. and Abbasi, S.A., 2014. The Generation, Impact and Management of E-Waste: State of the Art. *Critical Reviews in Environmental Science and Technology*. **44(14)**, 1577–1678.

Ramachandra, T.V. and Saira Varghese, K., 2004. Environmentally sound options for e-wastes management. *Envis Journal of Human Settlements*, March.

Sheng, P.P. and Etsell, T.H., 2007. Recovery of gold from computer circuit board scrap using aqua regia. *Waste Management Research*, **25(4)**, 380–383.

Terazono, Atsushi, Shinsuke Murakami, Naoya Abe, Bulent Inanc, Yuichi Moriguchi, Shin-ichi Sakai, Michikazu Kojima, Aya Yoshida, Jinhui Li, Jianxin Yang, Ming H. Wong, Amit Jain, In-Suk Kim, Genandrialine L. Peralta, Chun-Chao Lin, Thumrongrut Mungcharoen and Eric Williams, 2006. Current status and research on E-waste issues in Asia. *Journal of Material Cycles & Waste Management*, **8**, 1–12.

UNEP, 2015. Report of the Conference of the Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal on the work of its twelfth meeting, Geneva.

Vats, M.C. and Singh, S.K., 2014. Status of E-Waste in India – A Review. *International Journal of Innovative Research in Science, Engineering and Technology*, **3(10)**, 16917–16931.

Veldbuizen, H. and Sippel, B., 1994. Mining discarded electronics. *Indian Environmental Society*, **17(3)**, 7.

Velgosova, O., Kadukova, J., Mrazikova, A., Blaskova, A., Petoczova, M., Harvathova, H. and Stofko, M., 2010. Influence of selected parameters on nickel bioleaching from spent nickel-cadmium batteries. *Mineralia Slovaca*, **42**, 365–368.

Wang, J., Bai, J., Xu, J. and Liang, B., 2009. Bioleaching of metals from printed wire boards by *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* and their mixture. *Journal of Hazardous Materials*, **172**, 1100–1105.

Wiaux, P., 1990. The recovery and recycling of metal utilizing electrolytic techniques. http://infohouse.p2ric.org/ref/29/28404.pdf.

Willner, J., Kadukova, J., Fornalczyk, A. and Saternus, M., 2015. Biohydrometallurgical methods for metals recovery from waste materials. *Metalurgija*. **54(1)**, 255–259.

Zakrewski, J., Chamer, R. and Koscielniak, A., 1992. Method for recovering gold and nickel from electronic scrap and waste. Polish Patent, PL158889B (C22B7/00).

Zhou, P., Zheng, Z. and Tie, J., 2005. Technological process for extracting gold, silver and palladium from electronic industry waste. *Chinese Patent*, CN1603432A (C22B 11/00).

Zhu, N., Zhang, L., Li, C. and Cai, C., 2003. Recycling of spent nickel-cadmium batteries based on bioleaching process. *Waste Management*. **23**, 703–708.

Chapter 13
Survey of Municipal Solid Waste (MSW) Treatment Methods and Compost Samples

B.R. Hiremath and Sudha Goel

1 Introduction

The unwanted, useless or used solid materials generated from combined residential, industrial and commercial activities are known as solid waste. As per the Municipal Solid Waste (Management & Handling Rules, 2000), garbage is defined as Municipal Solid Waste which includes commercial and residential wastes generated in municipal or notified areas in either solid or semi-solid form excluding industrial hazardous wastes but including treated bio-medical wastes. Municipal solid waste consists of household waste, construction and demolition debris, sanitation residue, and waste from streets.

The Census of 2011 estimates India's population to be 1.21 billion which is 17.66% of the world population. Increasing population levels, rapid economic growth and rise in community living standard accelerates the generation rate of municipal solid waste (MSW) in Indian cities (Sharholy et al. 2007). India's urban population was 285 million in 2001 and increased to 377 million in 2011. CPCB lists 366 cities which represent 70% of India's urban population and generate 130,000 tons per day (TPD) or 47.2 million tons per year (TPY) at a per capita waste generation rate of 500 g/day. The solid waste generated in any area is generally directly dependent on the economy and the percentage of urban population.

B.R. Hiremath (✉)
Civil Engineering Department, Basaveshwar Engineering College, Bagalkot 587102,
Karnataka, India
e-mail: brhiremath1@gmail.com

S. Goel
Civil Engineering Department, Indian Institute of Technology Kharagpur,
Kharagpur 721302, WB, India

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_13

Organic waste composting is one of the best methods for treating MSW and is a viable alternative to landfilling and incineration (Ribeiro et al. 2000; Rosen et al. 1993; Soumare et al. 2003; Manios 2004; Adani et al. 2004). Aerobic composting is defined as the decomposition of organic materials in the presence of oxygen. Since composting leads to a stabilised final product, which will improve soil quality and fertility, it is one of the best options for organic waste disposal among the various strategies of waste management. The specific carbon-to-nitrogen ratio and the moisture content may increase the effectiveness of the process of composting (Chang and Chen 2010; Kumar et al. 2010). Factors like feed composition, moisture content, oxygen content, temperature, and pH affect the process of composting and these parameters may also affect microbial activities (Bhatia et al. 2013). Bulking agents like rice husk, sawdust and rice bran increase the quality of food waste (Chang and Chen 2010). Urea addition in crop waste was in practice in the past to reduce the C/N ratio (Gaind and Gaur 2000), but in recent practice, nitrogen-rich organic wastes are being used in organic farming for which poultry litter and cow dung wastes are supplements (low C/N ratio <12) (Kalemelawa et al. 2012).

A survey was conducted using the Internet to determine the most common MSW treatment methods adopted commercially. Further, a quantitative and qualitative analysis of eleven different compost samples from different parts of India was done based on laboratory elemental analysis.

2 Materials and Methods

2.1 Data Collection

A list of composting companies in India with Internet addresses was available for www.compost-india.com. An analysis of composting companies, and their products in India was done to determine the following factors: number of composting companies in each state, raw materials used, cost per kg of compost, if compost quality was tested, and method of composting. Eleven compost samples were also collected and tested for their elemental composition and their description is given in Table 13.1.

2.2 Measurement and Analysis

Moisture content, bulk density, total solids (TS), volatile solids (VS) and fixed solids (FS) were measured according to standard methods. Scanning electron microscope (ZEISS EVO 60, Carl ZEISS SMT, Germany) images were used to obtain information about the sample's surface topography. Also, Energy Dispersive

Table 13.1 Compost samples and their description

S. No.	Composts	Description
1	BHR 2	Bhadreswar Compost (Vermi-compost)
2	DHP 2	Dhapaland Compost (Windrow)
3	AHD	Ahmedabad Compost (Compost)
4	AGR	Agriculture Gross Compost (Vermi-compost)
5	BGK 1	Bagalkot Compost 1 (Vermi-compost)
6	BGK 2	Bagalkot Compost 2 (Vermi-compost)
7	HC	Kharagpur Home Compost
8	NPC	Neem Patta Compost
9	BMC	Bone Meal Compost
10	OC 1	Orissa Compost 1
11	OC 2	Orissa Compost 2

X-ray Spectroscopy (EDX) was performed to determine elements in or on the surface of the samples for qualitative information about compost composition.

3 Results and Discussion

3.1 Survey Report

The results of the Internet survey are shown in Fig. 13.1 and the largest numbers of companies are in Karnataka State (26). Compost companies use their products for different purposes like soil conditioner, mulch, growing media, and top soil constituents.

Compost companies produce various types of composts like commercial compost, vermicompost, farm/manure compost, mixed municipal compost, and forest/woodchip compost. Most of the compost companies use green waste or kitchen waste as their raw material (54%) and they also use plant waste and animal excreta as shown in Fig. 13.2.

3.2 EDX Report

It is necessary to determine the elements present in compost to determine the quality and applicability for agricultural purposes. Elemental analysis of essential nutrients like C, O, N, P, K and S present in the compost samples was carried out for 11 samples and the percent composition is depicted in the bar chart (Fig. 13.3).

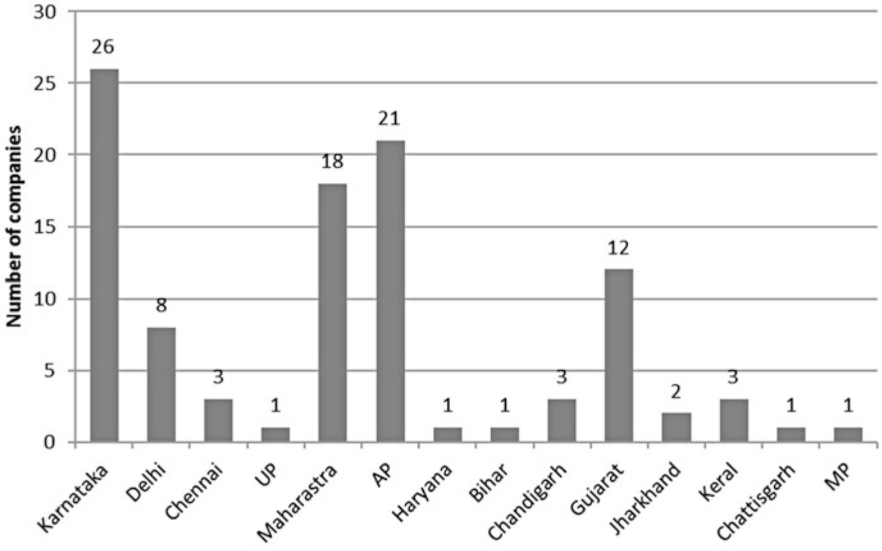


Fig. 13.1 State-wise distribution of composting companies in India

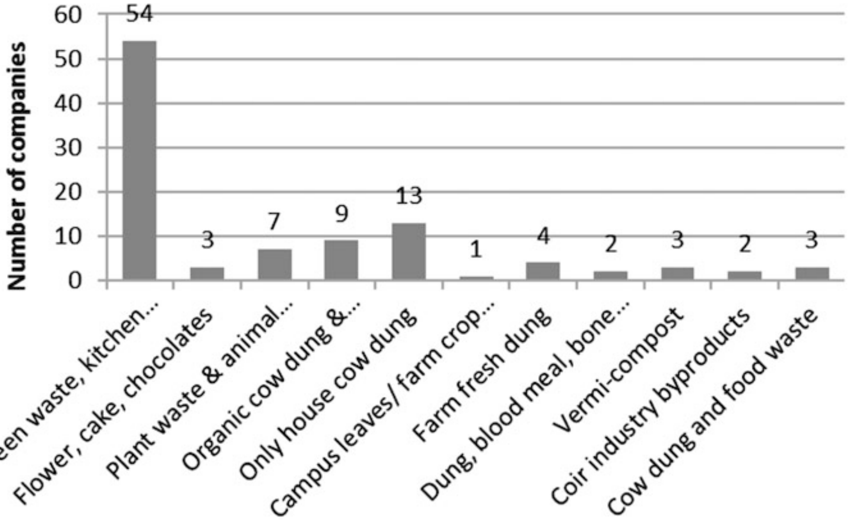


Fig. 13.2 Number of companies using different raw materials for compost generation

- All compost samples in the present study have abundant quantity of oxygen. Maximum quantity of oxygen was found in OC1 (46.33%), whereas lowest quantity of oxygen was observed in DHP2 (33.16%).

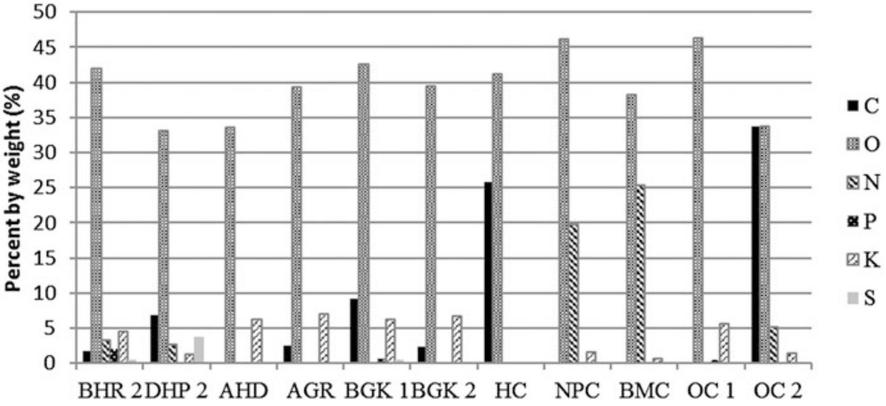


Fig. 13.3 Essential elements present in compost samples

- Essential nutrients like C, N, P and K are in low quantities in most of the compost samples (Fig. 13.3).
- Some metals are also found in composts (Mn, Mg, Cu, Pb, Hg and Cr) but in less than detectable quantities. Metals like Al, Si, Fe, K, Zn and Ti were found to be more than 2% by total percentage weight of elements in compost samples (Fig. 13.4). Sample AGR had the highest percentage (11%) of aluminium and BMC had the least (1%). Other metals like Fe and K were found in almost all samples whereas Zn and Ti were found in BHR 2, DHP 2 and AHD in small quantities.
- As all composts contain soil, large amounts of silica were found in all composts (35.62% in OC2 and 13.14% in NPC).

SEM images of Neem Patta compost and Bone Meal compost are shown in Figs. 13.5a and 13.5b. Both images show the granular nature of compost particles. The sizes of the grains vary from 1 to 2 microns and are likely to be silica nodules based on EDX analyses and other observations (Phutela and Sahni 2013).

4 Conclusions

Composting is one of the best methods of recycling organic materials. The objective of this study was to do a quantitative and qualitative analysis of composts in India through an Internet survey and laboratory elemental analysis. Eleven compost samples were collected and tested for their elemental composition. The elemental analysis report shows that essential nutrients like N, P and K are in less than required quantities which indicate poor compost quality. Major conclusions from this study were:

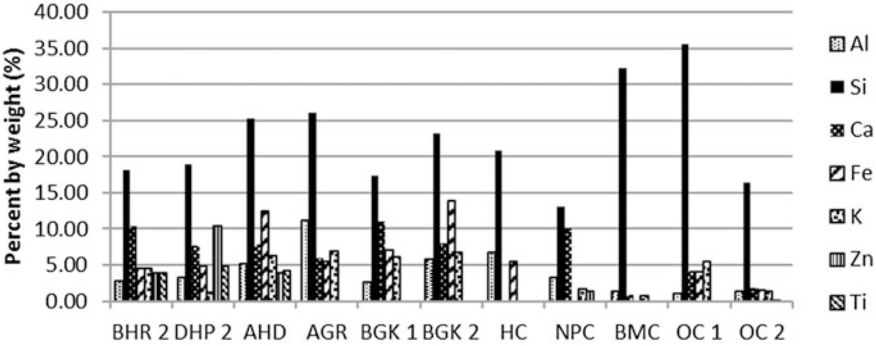


Fig. 13.4 Metals present in compost samples

Fig. 13.5a Neem Patta compost

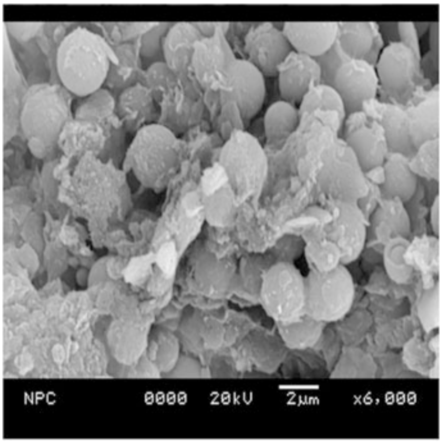
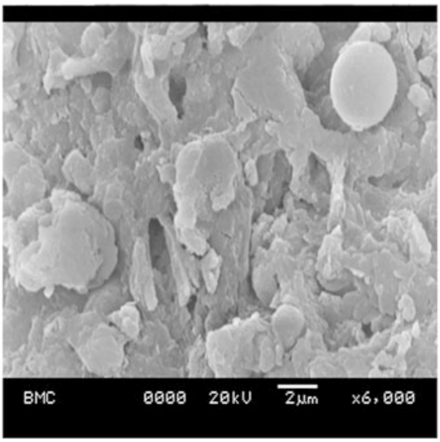


Fig. 13.5b Bone Meal compost



- The largest numbers of compost companies (with Internet addresses) were in Karnataka.
- Most composting numbers of companies use green waste and kitchen waste for composting.
- Compost companies produces different types of composts like commercial.l compost, vermicompost, farm/manure compost, mixed municipal compost, and forest/woodchip compost.
- The composts sampled in this study are not harmful for use in agriculture. However, these compost samples are of poor quality due to their low nutrient levels.
- Compost samples have some metals in their elemental composition in small quantity.

References

Adani, F., Tambone, F. and Gotti, A., 2004. Biostabilization of municipal solid waste. *Waste Management*, **24**, 775–783.

Bhatia, A., Madan, S., Jitendra, S., Muntjeer, A. and Pathania, R., 2013. Diversity of bacterial isolates during full scale rotary drum composting. *Waste Management*, **33**, 1595–1601.

Chang, J.I. and Chen, Y.J., 2010. Effects of bulking agents on food waste composting. *Bioresource Technology*, **101**, 5917–5924.

Gaind, S. and Gaur, A.C., 2000. Quality assessment of compost prepared from fly ash and crop residue. *Bioresource Technology*, **87**, 125–127.

Kalemelawa, F., Nishihara, E., Endo, T., Ahmad, Z., Yeasmin, R., Tenywa, M.M. and Yamamoto, S., 2012. An evaluation of aerobic and anaerobic composting of banana peels treated with different inoculums for soil nutrient replenishment. *Bioresource Technology*, **126**, 375–382.

Kumar, M., Ou, Y.L. and Lin, J.G., 2010. Co-composting of green waste and food waste at low C/N ratio. *Waste Management*, **30**, 602–609.

Manios, T., 2004. The composting potential of different organic solid wastes: Experience from the island of Crete. *Environment International*, **29**, 1079–1089.

Phutela, U.G. and Sahni, N., 2013. Microscopic Structural Changes in Paddy Straw Pretreated with Trichoderma reesei MTCC 164 and Coriolus versicolor MTCC 138. *Indian Journal of Microbiology*, **53**, 227–231. doi:10.1007/s12088-012-0321-8.

Ribeiro, H., Vasconcelos, E. and Dos Santos, J.Q., 2000. Fertilisation of potted geranium with municipal solid waste compost. *Bioresource Technology*, **73**, 247–249.

Rosen, C., Halbach, T. and Swanson, B., 1993. Horticultural uses of municipal solid waste composts. *HorTechnology*, **3**, 167–173.

Sharholy, M., Ahmad, K., Vaishya, R.C. and Gupta, R.D., 2007. Municipal solid waste characteristics and management in Allahabad, India. *Waste Management (New York, N.Y.)*, **27(4)**, 490–496. doi:10.1016/j.wasman.2006.03.001.

Soumare, M., Tack, F.M.G. and Verloo, M.G., 2003. Characterisation of Malaysian and Belgian solid waste composts with respect to fertility and suitability for land application. *Waste Management*, **23**, 517–522.

Chapter 14
Development and Application of a Multi-Criteria Decision Making (MCDM) Tool for Solid Waste Management: Kolkata as a Case Study

Tumpa Hazra, Bhargab Maitra, and Sudha Goel

1 Introduction

Solid Waste Management (SWM) is a major challenge for developing countries due to rapid increase in Solid Waste (SW) generation rates and financial constraints for proper management. Poorly managed SW causes severe consequences to society like financial and aesthetic degradation, environmental pollution and is a serious health hazard. SWM consists of six functional elements: generation, storage, collection, transfer, processing or treatment and disposal. Current regulations hold the administrative, i.e., municipal authority responsible for SWM and all expenditure on collection, transfer, processing and disposal of SW has to be met using the financial resources available. The main sources of revenue for any municipal authority are municipal or property tax and octroi. In a survey of municipal budgets and revenues for five major cities in India, 38 to 83% of the revenues were derived from these sources (Sekhar and Bidarkar 2013). Non-tax revenue, grants and other contributions formed the remaining part of the total revenues. In general, policy makers prepare SWM plans by optimizing expenditure on collection, transfer, processing and disposal of SW which is proportionate to municipal tax based on direct costs to households. Additional expenditure to be incurred by the municipal authority in improving the system has to be recovered from the community as additional municipal tax. Also, any savings by the municipal authority are transferred to the households in terms of tax relief. However,

T. Hazra (✉)
Civil Engineering Department, Jadavpur University, Kolkata 700 032, India
e-mail: tumpa_hazra@yahoo.com

B. Maitra • S. Goel
Civil Engineering Department, Indian Institute of Technology Kharagpur,
Kharagpur 721302, WB, India

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_14

these SWM plans fail to account for inconvenience costs to users and environmental costs.

The objective of the present work was to develop a Multi-Criteria Decision Making (MCDM) tool to evaluate different SWM alternatives and recommend the best alternative based on an analysis of Total Costs, i.e., direct, indirect and environmental costs. The direct costs of SWM to households were minimized by developing a Linear Programming (LP) model for suitable allocation of wastes from multiple collection points to multiple disposal sites. Indirect costs to households primarily depend on the functional elements or attributes of the SWM system such as type of collection, frequency of collection, type of vehicle used for collection/transfer, etc. Costs associated with inconvenience of the SWM system was calculated by analyzing behavioural data collected from households in terms of the households' Willingness-to-Pay (WTP) (Hazra et al. 2013). Costs associated with environmental damage and management were estimated based on another study done by California Integrated Waste Management Board (CIWMB) and Tellus Institute (1991) as referred to in Rathi (2006). Several SWM alternatives were developed by changing one or more functional elements of SWM system and their levels. The best alternative was considered to be the one that gave maximum net benefits to households in terms of direct and indirect costs including environmental costs. This MCDM tool was applied to the Kolkata Municipal Corporation (KMC) area and policy recommendations are provided based on these results.

2 Linear Optimization Model

A linear optimization model was developed to minimize expenditure of KMC on collection and transfer, processing and disposal of SW and environmental costs of facility sites by suitably allocating wastes from multiple collection points to multiple facility sites. The constraints are mass balance constraints, capacity limitation constraints and non-negativity constraints.

2.1 Objective Function

The objective function was to minimize expenditure and environmental costs of SWM by suitably allocating waste from multiple collection points to multiple facility sites (aerobic compost plant and sanitary landfill). The expenditures/incomes which were considered during model development are: (i) expenditure related to waste management at aerobic compost plant (C_a), (ii) expenditure related to waste management at sanitary landfill (C_1), (iii) income from selling of compost (R_c) and (iv) income from selling of recyclable materials (R_r). Each expenditure component (i.e., C_a and C_1) again includes expenditure towards waste transfer (t_c), cost of land for facility site (l_c), operational cost for facility site (o_c) and environmental cost for waste management of each facility site (e_c). The decision variables are X_{ij}, i.e., amount of waste transferred from ith collection point to jth facility site.

The mathematical expression of the objective function is:

Minimize (C – R) where C = Total expenditure related to all aerobic compost plants, and sanitary landfills, and R = Total income from selling compost and recyclable materials.

The total expenditure of waste management at all aerobic compost plants $\left(\sum_{a=1}^{m} C_a\right)$ consists of Eqs. (14.1a, 14.1b, 14.1c, and 14.1d):

$$\begin{aligned}\text{Total transfer costs} &= \sum_{i=1}^{n}\sum_{a=1}^{m} d_{ia} \times t_c \times X_{ia} \\ &\quad + \sum_{a=1}^{m}\sum_{l=1}^{k} + d_{al} \times t_c \times X_{al}\end{aligned} \tag{14.1a}$$

$$\begin{aligned}\text{Total site operation costs} &= \sum_{i=1}^{n}\sum_{a=1}^{m} o_c^{ac} \times X_{ia} \times f_b \\ &\quad + \sum_{a=1}^{m}\sum_{l=1}^{k} o_c^{sl} \times X_{al}\end{aligned} \tag{14.1b}$$

$$\begin{aligned}\text{Total land costs} &= \sum_{i=1}^{n}\sum_{a=1}^{m} l_c^{ac} \times X_{ia} \times f_b \\ &\quad + \sum_{a=1}^{m}\sum_{l=1}^{k} l_c^{sl} \times X_{al}\end{aligned} \tag{14.1c}$$

$$\begin{aligned}\text{Total environmental costs} &= \sum_{i=1}^{n}\sum_{a=1}^{m} e_c^{ac} \times X_{ia} \times f_b \\ &\quad + \sum_{a=1}^{m}\sum_{l=1}^{k} e_c^{sl} \times X_{al}\end{aligned} \tag{14.1d}$$

The total expenditure of waste management at all sanitary landfills $\left(\sum_{i=1}^{k} C_l\right)$ consists of Eqs. (14.2a, 14.2b, 14.2c, and 14.2d):

$$\text{Total transfer costs} = \sum_{i=1}^{n}\sum_{l=1}^{k} d_{il} \times t_c \times X_{il} \tag{14.2a}$$

$$\text{Total operation costs} = \sum_{i=1}^{n}\sum_{l=1}^{k} o_c^{sl} \times X_{il} \tag{14.2b}$$

$$\text{Total land costs} = \sum_{i=1}^{n}\sum_{l=1}^{k} l_c^{sl} \times X_{il} \tag{14.2c}$$

$$\text{Total environmental costs} = \sum_{i=1}^{n}\sum_{l=1}^{k} e_c^{sl} \times X_{il} \tag{14.2d}$$

Therefore total cost C is calculated using Eq. 14.3

$$C = \sum_{a=1}^{m} C_a + \sum_{l=1}^{k} C_l \tag{14.3}$$

where X_{ij} = amount of waste transferred from ith collection point to jth facility site, n = number of collection points, $n = 15$; X_{ia} = amount of waste transferred from ith collection point to aerobic compost plant; X_{al} = amount of waste transferred from aerobic compost plant to sanitary landfill site; X_{il} = amount of waste transferred from ith collection point to sanitary landfill site; a = aerobic compost plant, m = number of aerobic compost plants, $m = 1$; C_a = total cost of aerobic compost plant; C_l = total cost of sanitary landfill, l = sanitary landfill from 1 to k and k = number of sanitary landfills, $k = 2$; d_{ia} = distance between collection points ‘i’

to aerobic compost plant ‘a’; d_{al} = distance between aerobic compost plant ‘a’ to sanitary landfill ‘l’; d_{il} = distance between collection points ‘i’ to sanitary landfill ‘l’; t_c = cost of waste transfer; f_b = fraction of biodegradable material in waste; ${o_c}^{ac}$ = operational cost per ton of waste at aerobic composting plant; ${o_c}^{sl}$ = operational cost per ton of waste at sanitary landfill ‘l’; ${l_c}^{ac}$ = cost of land associated with aerobic composting ‘a’; ${l_c}^{sl}$ = cost of land associated with sanitary landfill ‘l’; ${e_c}^{ac}$ = environmental cost per ton of waste for aerobic composting plant ‘a’ and ${e_c}^{sl}$ = environmental cost per ton of waste for sanitary landfill ‘l’.

The total income from selling compost produced at all aerobic compost plants is calculated using Eq. 14.4:

$$\sum\nolimits_{a=1}^{m} R_a = \sum\nolimits_{i=1}^{n} \sum\nolimits_{a=1}^{m} f_b \times p_c \times X_{ij} \times r_a \tag{14.4}$$

The total income from selling recyclables materials is calculated using Eq. 14.5:

$$\sum\nolimits_{r=1}^{m+k} R_r = \sum\nolimits_{i=1}^{n} \sum\nolimits_{j=1}^{m+k} f_r \times X_{ij} \times r_r \tag{14.5}$$

Therefore, total income R is calculated using Eq. 14.6,

$$R = \sum\nolimits_{a=1}^{m} R_a + \sum\nolimits_{r=1}^{m+k} R_r \tag{14.6}$$

where R_a = income from selling compost; R_r = income from selling recyclables-wet (milk packets, water bottles, etc.); R = total income from selling compost and recyclable materials; p_c = compaction factor for aerobic compost plant; r_a = income from per ton of aerobic compost; f_r = fraction of recyclable (wet) materials ‘r’ in waste and r_r = income from per ton of recyclable materials ‘r’.

2.2 Constraints

2.2.1 Mass Balance Constraint

All solid waste collected at any collection point ‘i’ should be transferred to facility sites. The mass balance constraint is written as Eq. 14.7:

$$\sum\nolimits_{i=1}^{n} \sum\nolimits_{a=1}^{m} X_{ia} + \sum\nolimits_{i=1}^{n} \sum\nolimits_{l=1}^{k} X_{il} = \sum\nolimits_{i=1}^{n} G_i \tag{14.7}$$

where G_i is the amount of waste collected at collection node ‘i’.

2.2.2 Capacity Limitation Constraint

Waste transferred to facility site should be less than or equal to the capacity of the facility site [Eqs. 14.8–14.9].

$$\sum_{i=1}^{n} \sum_{a=1}^{m} f_b \times X_{ia} \leq Cap^{ac} \tag{14.8}$$

$$\sum_{a=1}^{m} \sum_{l=1}^{k} X_{al} + \sum_{i=1}^{n} \sum_{l=1}^{k} X_{il} \leq Cap^{sl} \tag{14.9}$$

where Cap^{ac} = capacity of aerobic compost plant 'a' and Cap^{sl} = capacity of sanitary landfill 'l'.

2.2.3 Non-negativity Constraint

All the decision variables should be greater than or equal to zero, i.e., X_{ia}, X_{al} and X_{il} are all ≥ 0.

2.3 Database

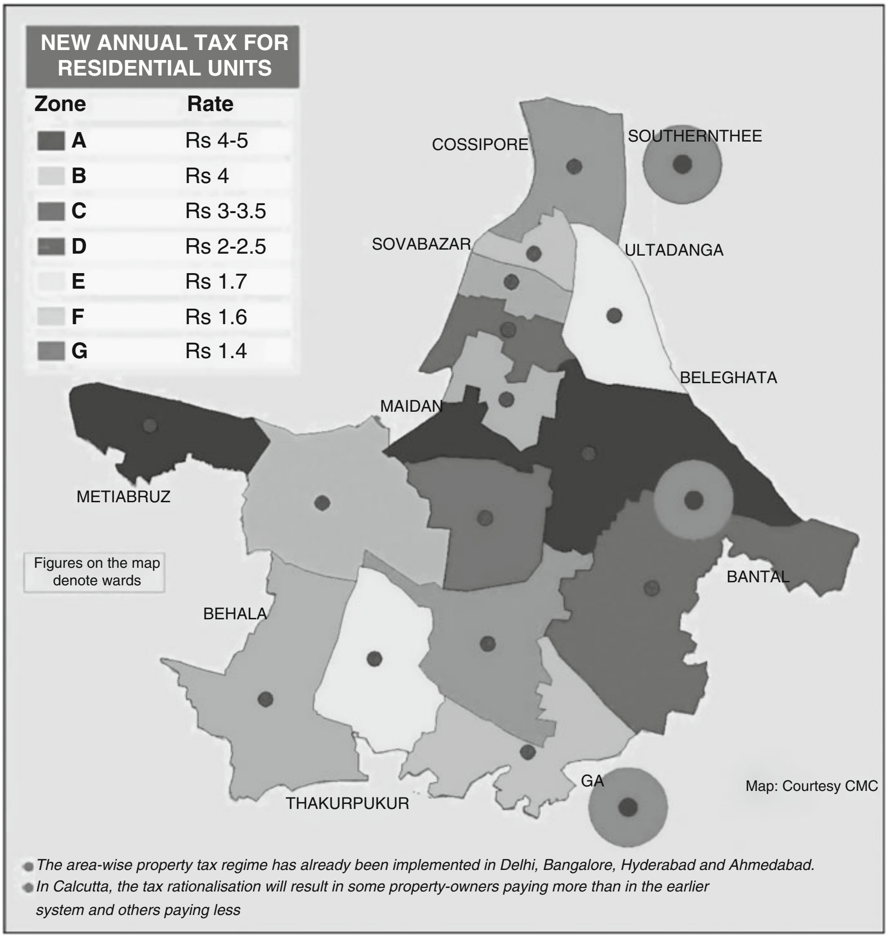
For administrative purposes, the KMC area is divided into 15 zones which are termed Boroughs. The central point of each Borough was considered to be a collection node. Therefore, the number of collection nodes was taken as 15. Three facility sites (one aerobic compost plant and two sanitary landfills) were considered for processing and disposal of solid waste. Numbers of decision variables and constraints is calculated below.

$$\begin{aligned} \text{Number of decision variables} &= n \times m + n \times k + m \times k \\ &= 5 \times 1 + 15 \times 2 + 1 \times 2 = 47 \\ \text{Number of constraints} &= 15 + 3 + 47 = 65 \end{aligned}$$

Figure 14.1 shows the 15 collection nodes and three facility sites. Data regarding SW collected in each node were obtained from KMC's office. The shortest distance from each collection node to each facility site was used for model development.

Composition of MSW and income derived from the different waste components are summarized in Table 14.1. Market prices of different recyclable waste components are shown in Column (A) and the SW composition of KMC area is shown in column (B). Depending on the market value, the income for KMC from different waste components is presented in Column (C) of Table 14.1.

The optimization model was solved for each of the various SWM alternatives (described in the next section) using MATLAB (2008).



- *The area-wise property tax regime has already been implemented in Delhi, Bangalore, Hyderabad and Ahmedabad.*
- *In Calcutta, the tax rationalisation will result in some property-owners paying more than in the earlier system and others paying less*

Fig. 14.1 Collection nodes and facility sites in KMC area

3 Solid Waste Management Alternatives and Their Evaluation

SWM consists of six functional elements and each functional element has different levels. By changing one or more levels of different functional elements, several alternatives of SWM system were developed. Table 14.2 summarizes different SWM functional elements and their levels (or attributes) for KMC area. It may be observed from Table 14.2 that there are 36 ($3 \times 2 \times 3 \times 2 = 36$) possible SWM alternatives which can be developed by combining different options for the six SWM activities (or functional elements): collection, collection frequency, transportation, segregation at home or by KMC, and finally, treatment and disposal.

Table 14.1 Components of waste of KMC area

Material	Market price of recyclables (₹ per Ton) (A)	Composition of KMC MSW (%) (B)	Income from recyclable waste (₹ per Ton) (C)
Paper	6000	6.07	364.2
Plastic	5000	4.88	244
Glass	5000	0.34	17
Metal	10,000	0.19	19
Organic	–	50.56	–
Other waste	–	37.96	–
Total			644.2

– unpublished

Three other alternatives: Present, Baseline-1 and Baseline-2 are also described in the following sections.

3.1 Present SWM Scenario

A schematic describing current SWM activities in the KMC area is shown in Fig. 14.2 and is termed as the 'Present' SWM alternative. Currently in KMC area, households dispose waste to KMC workers coming for waste collection (door-to-door collection). At present, no segregation of waste is done at home. KMC workers collect wastes from door-to-door by open hand cart or tricycle at moderate frequency. Collected wastes are then transferred by open tipper truck directly to the Dhapa disposal site. The wastes are then disposed in the open landfill in Dhapa without any treatment. An aerobic compost plant of capacity 700 tons/day exists at Dhapa landfill site. However, it is no longer functioning since wastes are not segregated in biodegradable and non-biodegradable parts.

At the time of developing the MCDM tool, official KMC estimates of municipal solid waste generation per day was 2906.3 tons/day. The landfill site at Dhapa is not sanitary and is almost exhausted in terms of its capacity (Hazra and Goel 2009).

3.2 Baseline SWM Scenarios

Two different baseline scenarios were defined and costs calculated for each. In both scenarios, door-to-door collection, moderate collection frequency, waste transportation in tipper trucks (without cover), and no segregation at home are assumed. The two scenarios differ from the present scenario in two main respects: segregation by KMC, treatment and disposal methods and plant capacities, as described below.

Table 14.2 Functional elements of a solid waste management system for KMC

Functional elements	Levels	Description
Collection	A	Door-to-door collection
	B	Community bin collection
	C	Private bin collection
Collection or clearance	D	High (daily collection)
Frequency	E	Moderate (alternate day collection)
Transportation	F	Tipper truck (uncovered)
	G	Dumper placer (covered)
Segregation by municipality	H	No segregation
	I	Segregation into two components (biodegradable and non-biodegradable)
	J	Segregation into three components (biodegradable, recyclable wet and rest)
Segregation at home	K	No segregation
	L	Segregation into two components (biodegradable and non-biodegradable)
	M	Segregation into three components (biodegradable, recyclable wet and rest)
Processing or disposal	N	Aerobic compost plant (700 ton/d capacity) & two landfill sites (1200 tons/d)
	O	Aerobic compost plant (1500 ton/d capacity) & two landfill sites (800 tons/d)
	P	Sanitary landfilling only

Baseline-1 In Baseline-1 scenario, for better solid waste management, wastes that are not taken for composting, i.e., $2906.3 - 700 = 2206.3$ tons/day were assumed to be disposed in two sanitary landfill sites, one in the North-East of the city (Landfill 1) and the other in the South of the city (Landfill 2) of capacities 1200 $\left(\cong \frac{2206.3}{2}\right)$ tons/day each; the landfill capacities are rounded-off to the nearest 100 tons/day, since an exact number would have no significance and excess capacity is better than exact capacity. Locations of the sanitary landfill sites were assumed on the basis of reconnaissance survey, secondary data and discussions with experts, city planners and municipal officers.

It was further assumed that non-segregated waste collected by KMC workers will be transferred to the Dhapa landfill site where KMC workers will segregate waste into three fractions (biodegradable, recyclable-wet and others). Biodegradable wastes will be treated at an aerobic compost plant (existing 700 tons/day capacity), the recyclable-wet fraction will be sold by KMC and the rest will be disposed in the two assumed sanitary landfills. This is termed as the 'Baseline-1' SWM alternative.

The biodegradable waste fraction for KMC area was found to be 50.56% (National Environmental Engineering Research Institute (NEERI) 1996).

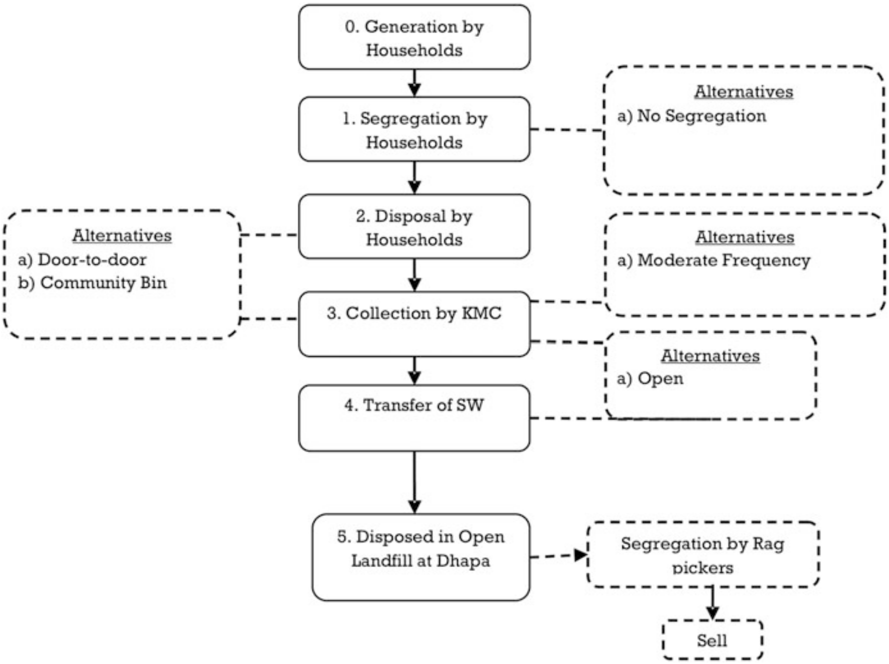


Fig. 14.2 Representation of present SWM system of KMC area

Therefore, the capacity of the aerobic compost plant that is required for processing all the biodegradable waste generated per day is (2906.3 × 0.5056) = 1470 tons per day.

Baseline-2 The present 700 tons per day capacity aerobic compost plant is not sufficient for processing all the biodegradable materials in MSW for KMC area. So, an additional scenario (Baseline-2) was created where the processing capacity of the aerobic compost plant was assumed to be 1500 tons per day and the capacity of each landfill site was assumed to be 800 [≅(2906.3–1500)/2] tons per day each. All other activity levels remain the same as Baseline-1.

Figure 14.3 schematically presents ‘Baseline-1 and Baseline-2’ alternatives for SWM system.

3.3 Evaluation of Alternatives

Evaluation of the various SWM alternatives was done by calculating the net benefits of each alternative as the difference in costs between the Baseline (Baseline-1) and each specific alternative *i*. The algorithm or flow chart used for evaluating different alternatives is shown in Fig. 14.4.

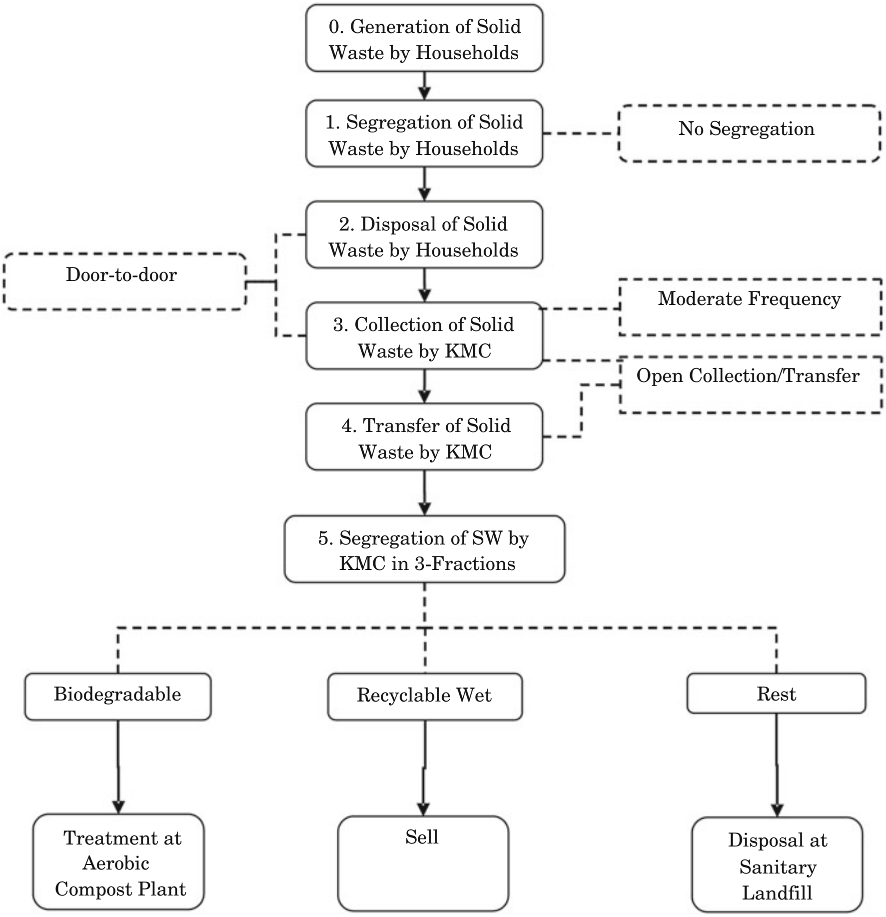


Fig. 14.3 Schematic representation of Baseline-1 and Baseline-2 alternatives for SWM system in KMC area

Step 0: Take the Baseline Alternative

The algorithm for evaluation of alternatives begins by assuming a ‘Baseline’ alternative for SWM system of KMC area as presented schematically in Fig. 14.4. Then direct cost (DC_B), indirect cost (IC_B) and environmental cost (EC_B) of the ‘Baseline’ alternative were calculated. Direct cost of collection was calculated based on the data provided by KMC officials (Table 14.3). Direct cost of transfer and processing of SW was calculated from the results obtained from the optimization model. Indirect cost (IC_B) of the waste management system was calculated from WTP values of the attributes related to the SWM system as shown in Table 14.4. Environmental cost of the ‘Baseline’ alternative (EC_B) was calculated

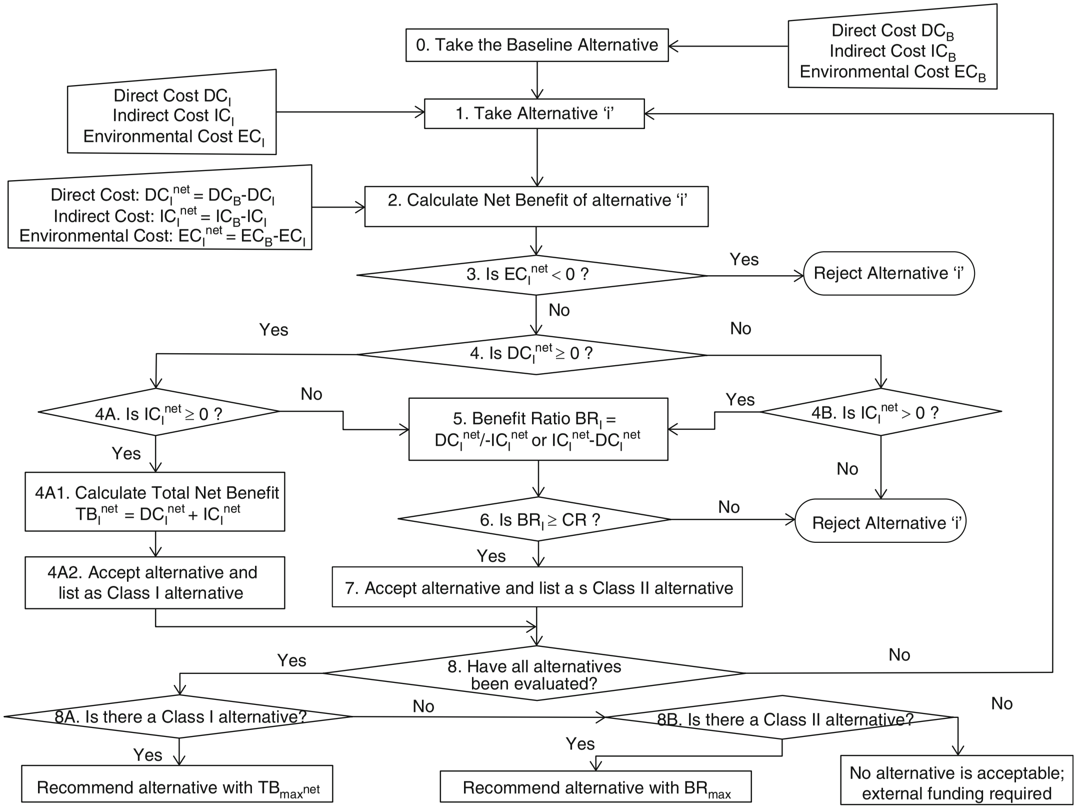


Fig. 14.4 Algorithm used for evaluating different SWM alternatives

Table 14.3 Direct costs of each SWM functional elements

Functional Elements	Description		Costs (₹ per Ton)
Collection	Baseline alternative (i.e. door-to door collection with moderate frequency)		300 Day^{-1}
	Door-to-door collection with high frequency		620 Day^{-1}
	Community bin collection with high frequency		85 Day^{-1}
	Private bin collection with high frequency		570 Day^{-1}
Transfer	Waste transfer by tipper truck		6.5 km^{-1}
	Waste transfer by dumper placer		11.5 km^{-1}
Processing in Aerobic Compost Plant	Land cost	Only biodegradable waste	730 Day^{-1}
		Mixed Waste	1435 Day^{-1}
	Segregation Cost	3-Fractions	792
		2-Fractions	396
	Operation cost	Only biodegradable waste	210 Day^{-1}
		Mixed Waste	426 Day^{-1}
Disposal in Sanitary Landfill	Land cost		790 Day^{-1}
	Operation cost		69 Day^{-1}

Table 14.4 WTP values for different SWM attributes (₹ Year/Household)

Walking time for disposal of waste by households	225.7 (Minute^{-1})
Covered instead of uncovered storage and transfer	176.9
No segregation instead of segregation into biodegradable and non-biodegradable fraction of waste at home	64
No segregation instead of segregation into biodegradable, recyclable wet and other fraction of SW at home	255
High frequency instead of moderate collection frequency of waste	194.25

from the optimization model using the environmental cost of different waste components as described in column (C) of Table 14.5.

Step 1: Take Alternative 'i'

From Table 14.2, it is obvious that 36 SWM alternatives can be developed by changing the level of one or more functional elements (like collection, transfer, segregation etc.) of SWM system. During evaluation, only one alternative was considered at a time. For any Alternative '*i*', direct cost (DC_i), indirect cost (IC_i) and environmental cost (EC_i) were calculated. All the cost components were calculated in terms of yearly municipal tax of households.

Table 14.5 Environmental cost of different waste components

Material	Envorinmental cost ($ per Ton)[a] (A)	Composition of KMC MSW (%)[b] (B)	Environmental cost of waste ($ per Ton) (C)
Landfill			
Paper	24.96	6.07	1.52
Plastic	43.84	4.88	2.14
Glass	11.27	0.34	0.04
Metal	53.06	0.19	0.1
Organic	23.66	50.56	11.96
Other waste	9.13	37.96	3.47
Composting			
Organics	18.29	50.56	9.25

[a] CIWMB (1991)
[b] NEERI (2005)

Step 2: Calculate Net Benefit of Alternative 'i' in Terms of Various Cost Components

After calculation of direct, indirect and environmental costs of 'Baseline' alternative and *i*th alternative, net benefits in terms of direct cost (DC_i^{net}), indirect cost (IC_i^{net}) and environmental cost (EC_i^{net}) were calculated by subtracting the direct (DC_i), indirect (IC_i) and environmental costs (EC_i) of the *i*th alternative from the direct (DC_B), indirect (IC_B) and environmental costs (EC_B) of 'Baseline' alternative.

Step 3: Check Environmental Sustainability, i.e., is $EC_i^{net} < 0$?

The environmental sustainability of an alternative was checked by calculating the net benefit in terms of environmental cost (EC_i^{net}), i.e., if the environmental cost of an alternative was more than that of the baseline then $EC_i^{net} < 0$, which means that alternative was rejected. Otherwise, that alternative was deemed to be environmentally sustainable and the next step was step 4.

Step 4: Check Direct Cost Suitability, i.e., is $DC_i^{net} \geq 0$

When the net benefit in terms of environmental cost (EC_i^{net}) was greater than or equal to zero, the net benefit in terms of direct cost (DC_i^{net}) was checked. Two outcomes are possible: if net benefit in terms of direct cost (DC_i^{net}) was greater than or equal to zero then the next step was step 4A, otherwise step 4B.

Step 4A: Check Indirect Cost Suitability, i.e., is $IC_i^{net} \geq 0$

When the net benefit in terms of direct cost (DC_i^{net}) was greater than or equal to zero, the net benefit in terms of indirect cost (IC_i^{net}) was checked. When it was found that the net benefit in terms of indirect cost (IC_i^{net}) was also greater than or equal to zero, then the next step was step 4A1, otherwise step 5.

Step 4A1: Calculate Total Net Benefit, i.e., TB_i^{net}

When the net benefit in terms of indirect cost (IC_i^{net}) was greater than or equal to zero, the total net benefit (TB_i^{net}) was calculated by adding net benefit in terms of direct cost (DC_i^{net}) and net benefit in terms of indirect cost (IC_i^{net}).

Step 4A2: Classify Alternative i as Class I Alternative if $TB_i^{net} \geq 0$

When the net benefit in terms of direct cost (DC_i^{net}) was greater than or equal to zero and the net benefit in terms of indirect cost (IC_i^{net}) was greater than or equal to zero, the total net benefit (TB^{net}) was also greater than or equal to zero. That alternative was then considered as one of the most desirable alternatives for recommendation in KMC area and was listed as a Class I alternative.

Step 4B: Check Indirect Cost Suitability when $DC_i^{net} < 0$, i.e., is $IC_i^{net} > 0$

When the net benefit in terms of direct cost (DC_i^{net}) was less than zero, the net benefit in terms of indirect cost (IC_i^{net}) was checked. When the net benefit in terms of indirect cost (IC_i^{net}) was found to be greater than zero then the benefit ratio was calculated in step 5. Otherwise, this alternative was rejected.

Step 5: Calculate Benefit Ratio and assume a reasonable Critical Ratio (CR)

The Benefit Ratio (BR) was calculated by dividing DC_i^{net} by IC_i^{net} for the following two cases. IC_i^{net} was multiplied by '–1' to get a positive benefit ratio (BR_i).

(a) When the net benefit in terms of direct cost (DC_i^{net}) was greater than or equal to zero and the net benefit in terms of indirect cost (IC_i^{net}) was less than zero,
(b) When the net benefit in terms of direct cost (DC_i^{net}) was less than zero and the net benefit in terms of indirect cost (IC_i^{net}) was greater than or equal to zero,

Critical Ratio (CR), which is basically the ratio of two net benefits, was an input used in the evaluation of alternatives where between the two components of benefit (i.e., direct and indirect), one was positive (or gain) and the other was negative (or loss). It was important to consider CR to ensure that whenever there is any negative benefit (or loss) in one component, the positive benefit in the other component is sufficiently large in order to make that alternative an acceptable one. It is common practice in transportation projects to charge the user an additional amount (as toll or charge) in lieu of improvements resulting in time savings and/or other benefits. In such cases, the additional toll or charge should logically be related to the perceived benefits to users from the improvement project and normally only a fraction of the perceived benefits is charged as toll. A comparable situation in improvement planning in SWM system will mean an acceptable CR of not merely greater than unity but sufficiently large, i.e., $CR >> 1$. There is no established norm for what fraction of benefits can be taken as additional user charge. This varies from country to country and organization to organization. For example, 25% of savings for cars and 60% of savings for trucks were used as tolls for Mumbai-Pune expressway in India. For improvement of taxies in Kolkata, an additional charge of upto 40% of the benefits resulting from replacement of old taxies by new ones was considered acceptable (Phanikumar and Maitra 2010). The CR values in each of these studies were 4, 1.7 and 2.5, respectively. Clearly, CR is a policy variable which should be higher than unity so that the net benefit (from changes in both direct and indirect costs) is positive. In the present work, CR is taken as 2.0 which is equivalent to charging a maximum of 50% of the net indirect benefit as direct cost to households as a policy.

Step 6: Check whether Benefit Ratio (BR_i) is greater than Critical Ratio (CR)

If Benefit Ratio (BR_i) for an alternative was greater than or equal to Critical Ratio (CR) then the next step was step 7. If not, that alternative was rejected.

Step 7: Classify Alternative i as Class II Alternative

When benefit ratio (BR_i) for an alternative was greater than or equal to critical ratio (CR), the alternative was accepted and was listed as a Class II alternative.

Step 8: Check if all 36 alternatives have been evaluated

If all alternatives had not been evaluated, the next step was step 1 to evaluate any remaining alternative. If all alternatives had been evaluated, next step was step 8A.

Step 8A: Is there a Class I alternative?

If yes, then the alternative with maximum total benefit ($TB_{max}{}^{net}$) was the recommended policy option. If no, then the next step was step 8B.

Step 8B: Is there a Class II alternative?

If yes, then the alternative with maximum benefit ratio (BR_{max}) was the recommended policy option. If no, then it is clear that none of the alternatives was acceptable and external funding would be required.

4 Calculation of Cost Components

4.1 Direct Costs

Direct cost to households is proportionate to the expenditure incurred by KMC towards SWM system. The annual expenditure incurred by KMC towards equipment, land or processing costs was calculated using Eq. 14.10:

$$A = \frac{I \times r}{1 - (1 + r)^{-n}} \tag{14.10}$$

where A = annualized cost of equipment or land; I = initial or capital cost, ₹; and n = life of equipment or land lease period, years; For handcarts or tricycles used for waste collection, 'n' value was assumed to be 5 years, whereas for tipper trucks and dumper placers used for transfer, 'n' value was taken as 15 years. r = rate of discount as percentage or interest to be paid on loan or cost of capital; 'r' was assumed to be 10%.

Net present value (NPV) for land was calculated based on Eq. 14.11:

$$\mathrm{NPV} = R_o + \frac{R_1}{(1+r)} + \frac{R_2}{(1+r)^2} + \cdots + \frac{R_{n-1}}{(1+r)^{n-1}} \tag{14.11}$$

where R = rent of land at time t; r = rate of discount at percentage, 'r' was assumed to be 10%; and n = land lease period, years; assumed to be 50 years.

Wages for manual workers were calculated based on the Government of India's Schedule of Minimum Wages for various activities including sweeping and cleaning in the State of West Bengal in 2011. According to the Schedule, wages may vary from ₹162.23 to 196.31/day, depending on their level of skills. For this study, minimum wages for workers were assumed to be ₹200/day.

The expenditure of KMC includes costs for collection and transfer of SW and also processing costs of SW (which includes operational cost and land cost) at different facility sites (aerobic compost plant and sanitary landfill). A summary of direct costs of each SWM functional element is shown in Table 14.3 (Hazra 2012).

For calculating income from compost and recyclables, it was assumed that the volume of compost produced is 25% of the volume of biodegradable waste. The selling price of compost was fixed at ₹3000/ton. This price is not based on the production cost of compost, but is a highly subsidized selling price to motivate farmers to buy it. Since KMC waste contains only 50.56% organics (NEERI 2005), the income from compost per ton of waste = 3000 × 0.5056 × 0.25 = 379.2 Rupees/ton.

4.2 *Indirect Costs*

Indirect costs associated with a SWM alternative were calculated using the Willingness-to-Pay (WTP) of households with respect to different quantitative attributes (walking time for disposal of waste by households and yearly municipal tax) and qualitative attributes (storage bin and transfer vehicle type, segregation of SW at home, collection frequency of waste from households or bins) (Hazra et al. 2015). Stated Choice (SC) data were collected from residents of KMC area in face-to-face interviews and 529 responses were included in the WTP analyses. The data were analyzed by developing Multinomial Logit (MNL) model and Random Parameter Logit (RPL) model using LIMDEP 8.0 (2005). All parameters except the cost parameter were assumed to follow constrained triangular distribution in the RPL model. A simulated maximum likelihood estimator using Halton draws with 500 replications was used to estimate the model parameters (Train 2000). 2464 refined observations were used for development of alternative models.

Several alternative models were attempted and models were accepted after reviewing the signs of the coefficient estimates, the statistical significance of coefficient estimates (Louviere et al. 2000) and log-likelihood ratio index (ρ^2) (Hensher et al. 2005). The marginal rates of substitution between the attributes and the costs are calculated by taking ratios between the coefficients of the attributes and the coefficient of the cost attribute. These values can be interpreted as marginal WTP for a unit change in each attribute under consideration. The details of estimating WTP values for different attributes of SWM system are presented in Hazra et al. (2013). A summary of WTP values which were used for calculation of indirect costs is given in Table 14.4.

Using the WTP values reported in Table 14.4, the indirect cost per household was calculated using Eq. 14.12:

$$IC_i = 225.7 \times t_i + cov_i + segre_i + fre_i \tag{14.12}$$

where IC_i = indirect cost of ith alternative, and t_i = the walking time of a household resident to the nearest disposal unit in minutes. t_i is zero for door-to-door collection and private bin collection systems and ₹225.7 is the indirect cost associated with walking to the nearest disposal unit per minute per year.

cov_i = indirect cost associated with the type of storage, collection and transfer vehicle used for SWM. cov_i is zero when storage, collection and transfer system is covered and cov_i is ₹176.7 per year when storage, collection and transfer system is uncovered.

$segre_i$ = indirect cost to household associated with the level of segregation of solid waste done. $segre_i$ is zero when no segregation of solid waste is done by households and $segre_i$ is ₹64 per year when solid waste is segregated by households in two components namely biodegradable and others. $segre_i$ is ₹255.0 per year when SW is segregated by households in three components namely biodegradable, recyclable-wet and other (Hazra 2012).

fre_i = indirect cost associated with frequency of collection of solid waste. fre_i is zero when collection/clearance frequency of waste is high and fre_i is ₹194.25 per year when collection/clearance frequency of waste is moderate.

4.3 Environmental Costs

Environmental costs of SW consist of environmental management cost and environmental damage cost due to processing of different SW components at different facility sites. Environmental management costs relate to environmental management activities and damage caused during collection, transportation, processing and disposal of SW. Environmental damage costs of different waste components have not been calculated for a developing country such as India. So, environmental costs were calculated as per CIWMB (1991) which was also referred in Rathi (2006). In Table 14.5, the environmental costs of different waste components calculated by CIWMB (1991) are presented in column (A) and the waste composition of KMC area is presented in column (B). Using the environmental cost of different waste components calculated by CIWMB (1991), environmental costs of each waste component in KMC area were calculated and are presented in column (C) in Table 14.5.

5 Results of Optimization Model

5.1 *Direct Costs*

The optimal direct costs of collection, transfer, segregation, processing, disposal and environmental costs of SWM for different alternatives are presented in Tables 14.6a and 14.6b.

From Table 14.6a, it is clear that irrespective of the collection system, the cost of transfer of SW from collection points to facility sites varies depending on the transfer vehicle and level of segregation at home. For the 'Present' alternative, i.e., actual conditions of KMC area, transfer cost is ₹3,79,009/day. If households segregate waste at home in two fractions (biodegradable and non-biodegradable), transfer cost of SW is reduced from ₹3,74,205 for Baseline-1 alternative to ₹3,54,490/day. When waste is segregated in three fractions at home, the transfer cost is further reduced to ₹3,10,961/day. The cost reduction is due to transfer of the biodegradable portion to the aerobic compost plant while other fractions are transferred to the sanitary landfill. The recyclable-wet fractions of wastes are sold from collection points without any transfer to processing sites. The processing cost of waste (including segregation cost of SW at facility sites, land cost and operation cost) is reduced with increase in segregation level of SW at home. Environmental costs of SWM at facility sites are also reduced from ₹21,57,090 to ₹18,89,927 per day if SW are segregated at home.

When households do not segregate SW at home, mixed waste comes to aerobic compost plant where KMC workers segregate it into three fractions. Biodegradable fractions are treated at the compost plant, recyclable portions are sold by KMC and other portions are transferred to sanitary disposal sites for disposal. However, when mixed wastes are transferred to sanitary landfill sites, it is disposed without any segregation. Therefore, only a fraction of the recyclable material is recovered in this management alternative and therefore, income from recyclable material is less. All the recyclable materials are recovered by KMC, when residents segregate wastes at home. This increases KMC's income from selling recyclable materials from ₹8,93,003 to ₹18,74,564/day. For the 'Present' alternative, although no segregation costs are required, the environmental costs (₹25,72,076/day) are maximum since non-segregated wastes are disposed into the landfill unscientifically.

Table 14.6b reveals that with increase in the capacity of aerobic compost plant (Baseline-2), transfer cost increased from ₹3,74,205 to ₹4,71,595/day and processing cost of SW also increased. For this case, all the biodegradable fractions are sent to aerobic compost plant which increases transfer costs. Since processing

Table 14.6a Direct cost components of SWM for different alternatives when capacity of aerobic compost plant is 700 Tons per Day

Alternatives	Transfer cost (₹/day)	Segregation cost (₹/day)	Operation cost (₹/day)	Land cost (₹/day)	Total direct cost (₹/day)	Environmental cost (₹/day)	Income (₹/day) from	
							Compost	Recyclables
Present situation	3,79,009	0	2,00,535	22,95,977	28,75,521	25,72,076	0	0
Baseline-1	3,74,205	10,96,524	2,88,230	26,27,657	43,86,616	21,57,090	5,25,002	8,93,003
Door-to-door collection/Community bin collection/Private bin collection with uncovered storage and transfer of waste								
No segregation of SW at home [Baseline-1]	3,74,205	10,96,524	2,88,230	26,27,657	43,86,616	21,57,090	5,25,002	8,93,003
Two levels segregation of SW at home	3,54,490	5,69,002	2,76,213	24,83,899	36,83,604	18,89,927	5,25,002	18,74,564
Three levels segregation of SW at home	3,10,961	0	2,76,213	24,83,899	30,71,073	18,89,927	5,25,002	18,74,564
Door-to-door collection/Community bin collection/Private bin collection with covered storage and transfer of waste								
No segregation of SW at home	6,62,055	10,96,524	2,88,230	26,27,657	46,74,466	21,57,090	5,25,002	8,93,003
Two levels segregation of SW at home	6,27,175	5,69,002	2,76,213	24,83,899	39,56,289	18,89,927	5,25,002	18,74,564
Three levels segregation of SW at home	5,50,162	0	2,76,213	24,83,899	33,10,274	18,89,927	5,25,002	18,74,564

Table 14.6b Direct cost components of SWM for different alternatives when all biodegradable waste is processed in compost plant

Alternatives	Transfer cost (₹/day)	Segregation cost (₹/day)	Operation cost (₹/day)	Land cost (₹/day)	Total cost (₹/day)	Environmental cost (₹/day)	Income, ₹/day	
							Compost	Recyclables
Present situation	3,79,009	0	2,00,535	22,95,977	28,75,521	25,72,076	0	0
Baseline-2	4,71,595	23,01,790	3,84,702	29,93,152	61,51,239	17,01,440	11,02,069	18,74,564
Door-to-door collection/Community bin collection/Private bin collection with uncovered storage and transfer of waste								
No segregation of SW at home	4,71,595	23,01,790	3,84,702	29,93,152	61,51,239	17,01,440	11,02,069	18,74,564
Two levels segregation of SW at home	3,79,093	5,69,002	3,84,702	29,80,178	43,12,975	16,99,879	11,02,069	18,74,564
Three levels segregation of SW at home	3,35,564	0	3,84,702	29,80,178	37,00,444	16,99,879	11,02,069	18,74,564
Door-to-door collection/Community bin collection/Private bin collection with covered storage and transfer of waste								
No segregation of SW at home	8,34,360	23,01,790	3,84,702	29,93,152	65,14,004	17,01,440	11,02,069	18,74,564
Two levels segregation of SW at home	6,70,703	5,69,002	3,84,702	29,80,178	46,04,585	16,99,879	11,02,069	18,74,564
Three levels segregation of SW at home	5,93,691	0	3,84,702	29,80,178	39,58,571	16,99,879	11,02,069	18,74,564

cost of aerobic compost plant is highest, processing cost for this alternative also increases. Environmental cost is reduced significantly from ₹57,090 to ₹17,01,440/day. On the other hand, income from compost (₹5,25,002 to ₹11,02,069/day) and recyclable materials (₹8,93,003 to ₹18,74,564/day) increased considerably.

5.2 Total Costs

All 36 alternatives were evaluated based on the algorithm presented in Fig. 14.4. These alternatives were developed by changing the level of only one attribute of Baseline-1 of the SWM system at a time. Of the 36 alternatives, only six alternatives were considered meaningful and are described below. Their results are summarized in Table 14.7.

- Alternative 1: Changing the collection frequency from moderate to high.
- Alternative 2: Using covered storage bins and transfer vehicles instead of uncovered.
- Alternative 3: Changing the collection system from door-to-door to community bin.
- Alternative 4: Changing the collection system from door-to-door to private bin.
- Alternative 5: Changing the segregation level at home from no segregation to two-level segregation (i.e. biodegradable and non-biodegradable).
- Alternative 6: Changing the segregation level at home from no segregation to three-level segregation (i.e., biodegradable, recyclable-wet and others).

No Class I alternative was found by changing the individual activity levels in the present KMC SWM system.

Table 14.7 Net benefit to households in terms of indirect cost and direct costs for selected alternatives considering change in one attribute only

Alternative	Net benefit in direct cost[a] (DC_i^{net})	Net benefit in indirect cost[a] (IC_i^{net})	Benefit ratio (BR_i)	Remarks
1	−23.1	15.9	0.68	$BR_i < CR$ hence rejected
2	−7.4	14.4	1.95	$BR_i < CR$ hence rejected
3	−20.2	0	0	$BR_i < CR$ hence rejected
4	18.7	−36.9	0.51	$BR_i < CR$ hence rejected
5	43.3	−5.2	8.33	Class-II alternative
6	59	−20.8	2.84	Class-II alternative

[a] in % of present municipal tax; CR = 2.0 in this study

Table 14.8 Net benefit to households in terms of direct costs and indirect cost for combined improvement strategy

	Two level segregation		Three level segregation	
	DTD	PB	DTD	PB
Net benefit in direct cost[a] (DC_i^{net})	12.1	16.1	29.7	32.7
Net benefit in indirect cost[a] (IC_i^{net})	25.1	25.1	9.5	9.5
Net benefit in environmental cost[a] (EC_i^{net})	6.8	6.8	6.8	6.8
Total net benefit[a] (TB_i^{net}), %	38.2	41.2	38.2	42.2
Classification of alternatives	Class-I	Class-I	Class-I	Class-I

Note: *DTD* Door-to-door collection, *PB* Private bin collection
[a] in % of present municipal tax

It is clear from Table 14.7 that of these six alternatives, only Alternatives 5 and 6 are Class II alternatives since the benefit ratio (BR_i) is greater than the Critical Ratio (CR). For the other four alternatives, the benefit ratio (BR_i) is less than the Critical Ratio (CR).

Since changing the levels of individual activities or attributes did not result in any Class I alternative, combinations of changes were developed for improvement of the present SWM system of KMC area which were then compared to the 'Baseline-1' alternative. The combinations of changes which provided maximum net benefit to households were:

(i) Door-to-door collection, high collection frequency, storage in covered bins, transferred through covered vehicles and segregation of SW in two fractions (biodegradable and non-biodegradable) at home.
(ii) Private bin collection, high collection frequency, storage in covered bins, transferred through covered vehicles and segregation of SW in two fractions (biodegradable and non-biodegradable) at home.
(iii) Door-to-door collection, high collection frequency, storage in covered bins, transferred through covered vehicles and segregation of SW in three fractions (biodegradable, recyclable-wet and other) at home.
(iv) Private bin collection, high collection frequency, storage in covered bins, transferred through covered vehicles and segregation of SW in three fractions (biodegradable, recyclable-wet and other) at home.

Results for these alternatives are summarized in Table 14.8. The net direct cost benefit (DC_i^{net}) and net indirect cost benefit (IC_i^{net}) to households due to these changes are also presented in Table 14.8. All the values are presented in terms of percentage of present municipal tax. Presently average yearly municipal tax for KMC area is ₹1222/household. During indirect cost estimation, it was assumed that the time taken to walk from households to community bins should not be more than 2 min.

Combined changes in different attributes of SWM system resulted in net positive benefits in terms of direct and indirect costs for both door-to-door collection and private bin collection for two-level and three-level of segregation of SW at home.

Table 14.9 Net benefit to households in terms of direct costs, indirect cost and environmental cost for different capacity compost plants

	700 TPD capacity compost		1500 TPD capacity	
	DTD	PB	DTD	PB
Net benefit in direct cost[a] (DC_i^{net})	13.1	16.1	11	14
Net benefit in indirect cost[a] (IC_i^{net})	25.1	25.1	25.1	25.1
Net benefit in environmental cost[a] (EC_i^{net})	6.8	6.8	11.7	11.7
Total net benefit[a] (TB_i^{net}), %	38.2	41.2	36.1	39.1
Classification of alternatives	Class-I	Class-I	Class-I	Class-I

IDTD Door-to-door collection, *PB* Private bin collection
[a] in % of present municipal tax

These are all Class I alternatives. So these alternatives may be recommended policy for KMC. Results of combined changes for community bin collection are not presented here since they are Class II alternatives where net direct cost benefit (DC_i^{net}) was positive and net indirect cost benefit (IC_i^{net}) was negative. The best management strategy based on direct, indirect and environmental costs is to have private bin collection along with high collection frequency, storage in covered bins, transferred through covered vehicles and segregation of SW in three fractions (biodegradable, recyclable-wet and other) at home.

The impact of increasing the waste processing capacity of compost plant from 700 tons per day to 1500 tons per day on households and the environment was also evaluated and the results are presented in Table 14.9.

From Table 14.9, it can be seen that an increase in compost plant capacity will reduce the net total benefit (TB_i^{net}) for both, private bin collection and door-to-door collection. However, for 1500 tons capacity compost plant, the environmental benefit was highest. Therefore, substantial net benefits in terms of direct, indirect and environmental costs will be obtained if capacity of the compost plant is enhanced.

5.3 *Policy Recommendations and Conclusions*

From an evaluation of various alternatives using the MCDM algorithm developed for this study, it was found that individual actions such as change in collection frequency, using covered storage containers and transfer vehicles, and change in collection systems failed to produce acceptable solutions since direct costs were too high compared to the gains in indirect costs. On the other hand, alternatives with segregation of SW in different fractions at home produced substantial benefits in terms of direct cost as compared to the loss in terms of indirect costs. Several superior solutions resulting in benefits both in terms of direct cost and indirect cost were obtained when two- or three-level segregation of SW at home were combined with changes in collection and transfer system of SW. The net benefits to the administrative authority can be transferred to households as tax rebate. Since Total Net Benefit is maximum (TB_{max}^{net}) for private bin collection with segregation of SW at home, private bin collection is the recommended option for KMC area. Total net benefits (TB_i^{net}) for private bin collection are very similar for both two-level (41.2% of the present yearly municipal tax) and three-level segregation (42.2% of the present yearly municipal tax) of SW at home. The basic difference is in distribution of benefits from direct and indirect costs. The benefit in terms of direct cost is maximum in 3-level segregation of SW at home while the benefit in terms of indirect cost is maximum in 2-level segregation of SW at home. At present, no segregation of SW is done by households in KMC area. Considering present practice of SWM system of KMC area, 2-level segregation of SW by households along with private bin collection system is recommended.

Once the recommended SWM system with 2-level segregation is found to work satisfactorily the direct benefit to households may be enhanced further by switching to 3-level segregation of SW at home. This sequential step is considered to be useful for bringing gradual change in behaviour of households in the context of carrying out segregation of SW at home. This measure has been adopted successfully in developed countries and in several cities in India.

The effect of change in capacity of aerobic compost plant on direct, indirect and environmental costs was also investigated. It was observed that an increase in the capacity of aerobic compost plant from 700 tons per day to 1500 tons per day would primarily result in substantial benefits in terms of environmental cost without much impact on direct and indirect costs. Therefore, enhanced capacity of the compost plant is the recommended option for KMC area.

An MCDM tool was developed in this study to evaluate different SWM alternatives considering not only direct costs to households but also indirect costs due to inconvenience of the system and environmental costs. Based on the evaluation process, recommendations were made for improvement planning of SWM system of the Kolkata Municipal Corporation (KMC) area.

Direct costs to households (basically municipal tax) are proportionate to expenditure of Municipal Authority for collection, transfer, processing and disposal of SW and environmental costs depend on methods of processing and disposal of SW. Hence a linear model was developed to minimize expenditure of transfer, processing and disposal of SW while considering environmental costs of facility sites by suitably allocating SW from multiple collection points to multiple facility sites.

Indirect costs to households which are due to inconvenience of the system are generally neglected in the management plans of developing countries. Behavioural analysis was carried out using Stated Choice (SC) data collected from residents of KMC area to calculate indirect costs associated with SWM alternatives in terms of WTP values of different SWM attributes, both qualitative and quantitative.

Environmental costs were calculated by considering different environmental values of SW components based on CIWMB (1991) as referred to Rathi (2006).

The MCDM tool presented in the paper may be used to evaluate different SWM alternatives considering direct and indirect costs and recommend better management policy for other cities or countries.

References

California Integrated Waste Management Board (CIWMB), and Tellus Institute, 1991. Disposal cost fee study. Retrieved from <http://www.calrecycle.ca.gov/publications/Documents/General%255C2011040.pdf> (6 July 2011).

Hazra, T., 2012. Improvement of solid waste management system considering direct and indirect cost. Ph.D. Thesis, IIT Kharagpur, India.

Hazra, T. and Goel, S., 2009. Solid waste management in Kolkata, India: Practices and challenges. *Waste Management*, **29(1)**, 470–478.

Hazra, T., Goel, S. and Maitra, B., 2013. Willingness-to-pay for solid waste management service attributes: Kolkata Municipal Corporation area, India, as a case study. *International Journal of Environment and Waste Management*, **12(4)**, 406–421.

Hazra, T., Goel, S. and Maitra, B., 2015. Willingness-to-pay and preference heterogeneity for service attributes of solid waste management: An experience in Kolkata, India. *Global NEST Journal*, **17(1)**, 82–92.

Hensher, D.A., Rose, J. and Greene, W., 2005. Applied choice analysis—A primer. Cambridge University Press, Cambridge, Mass.

Louviere, J.J., Hensher, D.A. and Swait, J.D., 2000. Stated choice methods, analysis and applications. Cambridge University Press, Cambridge, Mass.

MATLAB, R., 2008. Licence Number 161051.

National Environmental Engineering Research Institute (NEERI), 1996. Strategy Paper on Solid Waste Management in India. <http://www.neeri.res.in>

National Environmental Engineering Research Institute (NEERI), 2005. Comprehensive Characterization of Municipal Solid Waste at Calcutta, India.

Phanikumar, C. and Maitra, B., 2010. Modelling Generalized Cost of Travel and Its Application for Improvement of Taxies in Kolkata. *ASCE Journal of Urban Planning and Development*, **136(1)**, 42–49.

Rathi, S., 2006. Alternative approaches for better municipal solid waste management in Mumbai, India. *Waste Management*, **26(10)**, 1192–1200.

Sekhar, S. and Bidarkar, S., 2013. Municipal Budgets in India: Comparison across Five Cities. *Economic and Political Weekly*, **34(20)**, 1202–1208.

Train, K., 2000. Halton sequences for mixed logits. Retrieved from <https://escholarship.org/uc/item/6zs694tp> (5 August 2010).

Chapter 15
Fundamentals of Microbiology

Tandra Mohanta, Deblina Dutta, and Sudha Goel

1 Introduction

While a large number of organisms are involved in the degradation of solid waste, microbes or micro-organisms constitute the biggest group. Other than vermicomposting, all bioprocesses for solid waste treatment are designed based on microbes, mostly bacteria and fungi. Microbes are defined as microscopic organisms that individually are too small to be seen by the naked human eye.

2 Classification of Living Organisms

All living organisms are made up of cells and can be broadly classified as prokaryotes and eukaryotes depending on differences in cell structure. All prokaryotes are unicellular, while eukaryotes can be unicellular or multicellular. Prokaryotes are also considered to be the most primitive organisms on an evolutionary basis. Fossil evidence suggests that prokaryotes were present 3.5 billion years ago while eukaryotes have been found only around 2 billion years ago (Madigan et al. 2015).

T. Mohanta
Advanced Technology Development Centre, Indian Institute of Technology Kharagpur,
Kharagpur 721302, India

D. Dutta
School of Environmental Science and Engineering, Indian Institute of Technology Kharagpur,
Kharagpur 721302, India

S. Goel (✉)
Civil Engineering Department, Indian Institute of Technology Kharagpur,
Kharagpur 721302, WB, India
e-mail: sudhagiitkgp@gmail.com

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1_15

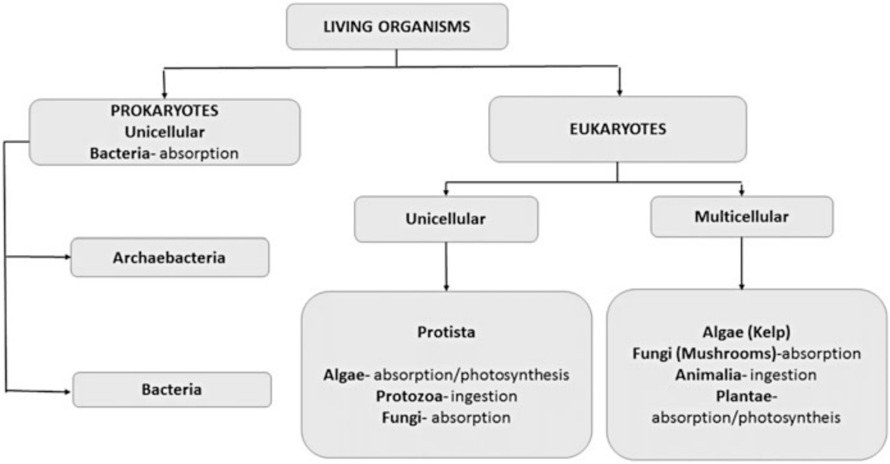


Fig. 15.1 Classification of micro-organisms and their modes of nutrition

Earlier when the number of species of living organisms that were known was limited, morphological differences were used as criteria to group organisms into two kingdoms – Plantae and Animalia. Later, R.H. Whittaker in 1969 proposed the five kingdoms of classification based on their modes of nutrition and other criteria. These five kingdoms include Monera (all bacteria or prokaryotes), Protista, Fungi, Plantae and Animalia (Whittaker and Margulis 1978). Whittaker's classification of organisms and their modes of nutrition are shown in Fig. 15.1 and a comparison is provided in Table 15.1. At the present time, organisms have been classified based on criteria such as cellular structure, mode of nutrition, and genetic characteristics. Current textbooks use a 3-kingdom classification based on similarities in ribosomal RNA: Archaea, Bacteria and Eukarya. Archaea bacteria are never pathogenic and all known bacterial pathogens are eubacteria or Bacteria (Tortora et al. 2010).

Besides bacteria, there are other organisms that are studied by microbiologists and cannot be classified as living by conventional definitions. These include:

Viruses Viruses are non-cellular, obligate, intracellular parasites. Outside the body of the host, they are non-living but inside the host they show characteristics of living organisms such as:

(a) Viruses have genetic material (DNA or RNA strands, but not both) that can be replicated and hence, can maintain heredity.
(b) The genetic material is enclosed in a protein coat called capsid. The capsid is made of subunits called capsomeres. The protein coat allows the virus to survive as a free particle in the environment, i.e., in non-living form, which becomes viable or vegetative only after infecting a host cell.
(c) The genetic material which is made of either DNA or RNA can mutate.

Table 15.1 Some defining characteristics of organisms in the five Kingdoms

	Kingdoms				
Characteristics	Monera	Protista	Fungi	Plantae	Animalia
Type of cell	Prokaryotic	Eukaryotic	Eukaryotic	Eukaryotic	Eukaryotic
Cell wall	Non-cellulosic (polysaccharide + amino acid)	Present in some	Present (chitin)	Present (cellulose)	Absent
Nuclear envelope or nucleus	Absent	Present	Present	Present	Present
Cellular organisation	Unicellular	Unicellular	Unicellular or Multicellular with loose tissue	Tissue/organ	Tissue/organ/ organ system
Mode of nutrition	Autotrophic: Chemoautotrophic and photoautotrophic; Heterotrophic (saprophytic/ parasitic)	Autotrophic: Photoautotrophic and Heterotrophic	Heterotrophic (saprophytic/ parasitic)	Autotrophic: Photoautotrophic	Heterotrophic: Holozoic/ saprophytic

Table 15.2 Principal differences between prokaryotic and eukaryotic cells

Characteristics	Prokaryotes	Eukaryotes
Size of cell	Typically 0.2–2.0 μm in diameter	Typically 10–100 μm in diameter
Nucleus	No nuclear membrane or nucleoli	True nucleus, consisting of nuclear membrane and nucleoli
Chromosome (DNA)	Single circular chromosome, lacks histones	Multiple linear chromosomes with histones
Membrane enclosed organelles	Absent	Present
Flagella	Consist of two protein building blocks	Complex, consist of multiple microtubules
Glycocalyx	Present as a capsule or slime layer	Present in some cells that lack a cell wall
Cell wall	Usually present, chemically complex (typical bacterial cell wall includes peptidoglycan)	When present, chemically simple
Plasma membrane	No carbohydrates and generally lacks sterols	Sterols and carbohydrates that serve as receptors present
Cytoplasm	No cytoskeleton or cytoplasmic streaming	Cytoskeleton, cytoplasmic streaming
Ribosomes	Smaller size (70s)	Larger size (80s), smaller size (70s) in organelles
Cell division	Binary fission	Mitosis
Sexual recombination	No meiosis, transfer of DNA fragments only (plasmid transfer)	Involves meiosis
Mitochondria	None	Mitochondria and/or chloroplasts are always present and contain ribosomes similar to those of prokaryotes

Source: Tortora et al. (2010)

Viroids Viroids are short strands of RNA without a protein coat.

Prions These are infectious particles comprising entirely of proteins and do not possess any nucleic acid. They were discovered by SB Prusiner in 1997 and are the cause of several neurological diseases in humans and animals such as mad cow disease (Tortora et al. 2010). Prions are the most resistant forms known at present and are capable of surviving conventional sterilization methods.

Differences Between Prokaryotes and Eukaryotes

Several characteristics are used to define differences between prokaryotic and eukaryotic organisms or cells and are summarized in Table 15.2.

Functions of Prokaryotic Structures

- Plasma membrane: It is a selectively permeable barrier which serves as the mechanical boundary of the cell through which nutrients and wastes are transported. It is the location of many metabolic processes (respiration, photosynthesis), and allows detection of environmental cues for chemotaxis.

- Gas vesicles or vacuoles: these provide the cell with buoyancy for floating in aquatic environments; they are very important for photosynthetic organisms like algae and green and purple photosynthetic bacteria that need to maximize their utilization of sunlight.
- Ribosomes: Ribosomes are sites for protein synthesis.
- Inclusion bodies: they are organelles for storage of carbon, phosphate, and other substances
- Nucleoid: since prokaryotes have no true nucleus, the cell volume occupied by genetic material, i.e., the single strand of DNA is called the nucleoid.
- Periplasmic space and periplasm: this is the space between the outer membrane and the cytoplasmic membrane which contains a gel-like fluid containing hydrolytic enzymes and binding proteins for nutrient processing and uptake (Tortora et al. 2010).
- Cell wall: the cell wall gives bacteria shape and protection.
- Capsule and slime layers: helps adhere to surfaces and provides resistance to phagocytosis.
- Fimbriae and pili: these help the cell to attach to surfaces. Pili help in bacterial mating (conjugation).
- Flagella are responsible for the ability of the cell to move in its environment.
- Endospore: Endospores are the dormant form of bacterial cells that allows them to survive under harsh environmental conditions; endospores have been known to survive from 34 years to 250 million years (Madigan et al. 2003) and are second only to prions in terms of resistance to chemical biocides (Tortora et al. 2010).

Functions of Eukaryotic Organelles

- Plasma membrane: it is a selectively permeable barrier which serves as a mechanical boundary of the cell through which nutrients and wastes are transported. It also mediates cell-cell interactions and adhesion to surfaces, and secretion of wastes and extracellular materials including enzymes.
- Cytoplasmic matrix: environment for other organelles, centre of many metabolic processes
- Microfilaments, intermediate filaments and microtubules: these are responsible for cell structure and movements and form the cytoskeleton.
- Endoplasmic reticulum (ER): ER is an extensive network of membranous sacs or tubules called cisterns and is continuous with the nuclear membrane (Tortora et al. 2010). ER can be of two types: rough or smooth ER. Rough ER has ribosomes attached to it and is the site of protein and membrane molecule synthesis. Smooth ER has no ribosomes attached to it but has unique enzymes which allow the synthesis of fats, lipids and hormones like oestrogen and testosterone.
- Golgi apparatus or Golgi complex: the first step in the transport of proteins from the ribosomes to other parts of the cell is through Golgi complexes which are stacks of ‘cisterns’ (Tortora et al. 2010). Proteins at the Golgi complex are moved through secretory or storage vesicles.
- Lysosomes: these are major storage vesicles which contain several powerful enzymes that are essential for intracellular digestion. In humans, white blood

cells which are an important part of the body's defense mechanism against bacteria and other 'foreign' particles or organisms, have large numbers of lysosomes (Tortora et al. 2010).

- Mitochondria: power house of the cell where energy production occurs through use of the tricarboxylic acid cycle, electron transport, oxidative phosphorylation, and various other pathways. It is capable of multiplying on its own by binary fission (Tortora et al. 2010).
- Chloroplasts: these are present in algae and green plants and are the site of photosynthesis. These are also capable of multiplying on its own by binary fission (Tortora et al. 2010).
- Nucleus: this is the repository for genetic information, i.e., DNA, and is the control centre for an individual cell.
- Nucleolus: site of ribosomal RNA synthesis, ribosome construction
- Cell wall: cell wall strengthens and gives shape to the cell.
- Cilia and flagella: these are responsible for cell movement
- Vacuoles: temporary storage and transport, digestion (food vacuoles), water balance (contractile vacuole).

3 Microbial Metabolism

All microbes take up dissolved compounds from their environment, use them for generating energy for maintenance and creating new biomass. During these metabolic activities of energy and biomass generation, waste and toxic substances are generated and are excreted into the environment as shown in Fig. 15.2.

Substrates

Both organic and inorganic compounds can serve as substrates for biomass and energy generation. Inorganic compounds include gases like O_2, CO_2 and dissolved compounds such as Fe^{2+}, NO_2^-, H_2S, H_2, and S.

Nutrients

Bacterial cells are generally assumed to be 70–90% water and the total weight of a single bacterial cell is assumed to be 1 picogram (pg, i.e., 10^{-12} g). Out of the 96 elements found in nature, only 26 are used by living organisms (Tortora et al. 2010). Analysis of

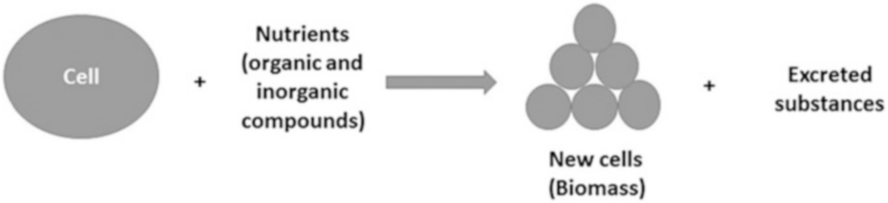


Fig. 15.2 Schematic representation of metabolism in microbes

Table 15.3 Typical composition of bacterial cells (Percentage of dry mass) (Metcalf and Eddy 2003)

Element	Range	Typical	Nutrient type
Carbon	45–55	50	Macronutrients
Oxygen	16–22	20	
Nitrogen	12–16	14	
Hydrogen	7–10	8	
Phosphorous	2–5	3	
Sulphur	0.8–1.5	1	
Potassium	0.8–1.5	1	
Sodium	0.5–2.0	1	
Calcium	0.4–0.7	0.5	Micronutrients
Magnesium	0.4–0.7	0.5	
Chlorine	0.4–0.7	0.5	
Iron	0.1–0.4	0.2	
All others	0.2–0.5	0.3	

microbial cell composition shows that more than 95% of the cell dry weight is made up of a few major elements defined as macronutrients (constituting >1% by dry weight): carbon (C), oxygen (O), hydrogen (H), nitrogen (N), sulphur (S), phosphorus (P), sodium (Na) and potassium (K) and is shown in Table 15.3 (Metcalf and Eddy 2003). Carbon constitutes more than 50% while N comprises about 13–14% of the dry weight of the cell. The first six nutrients or elements (C, O, H, N, S, and P) are components of carbohydrates, lipids, proteins, and nucleic acids. Carbohydrates and lipids are mainly composed of C, H and O while proteins additionally contain N and S. Nucleic acids, besides the first five elements, have a large component of P. The remaining two macronutrients exist in the cell as cations and play a variety of roles. Sodium (Na) is an essential nutrient for some organisms especially marine organisms. Potassium (K^+) is required for activity by a number of enzymes, including some of those involved in protein synthesis.

All organisms, including microorganisms, require several micronutrients or trace elements. Micronutrients, defined here as those required in <1% by dry weight of the cell, include calcium, magnesium, iron, manganese, zinc, cobalt, molybdenum, nickel, and copper, and are needed by most cells. Calcium (Ca^{2+}), among other functions, contributes to the heat resistance of bacterial endospores. Magnesium (Mg^{2+}) serves as a cofactor for many enzymes, complexes with ATP, and stabilizes ribosomes and cell membranes. Iron (Fe^{2+} and Fe^{3+}) is a part of cytochromes and a cofactor for enzymes and electron-carrying proteins (Madigan et al. 2015).

3.1 *Classification of Organisms Based on Food and Energy Sources*

All organisms require nutrients and energy for growth and reproduction. There are two ways of classifying organisms. Organisms can be classified based on either carbon (C)-sources or energy sources.

Based on carbon sources, organisms can be either autotrophs (meaning self-feeding) or heterotrophs (meaning other-feeding). Autotrophs convert inorganic C (mainly carbon dioxide) to organic carbon or biomass, while heterotrophs convert organic C (mainly other organisms or dead detrital matter) to other forms of organic carbon or new biomass. Plants and phytoplankton are examples of autotrophs while all organisms that consume other living organisms are examples of heterotrophs.

Based on energy sources, organisms can be either phototrophs or lithotrophs. Phototrophs derive their energy from light and include all photosynthetic organisms like plants, and algae. Many pigmented bacteria like cyanobacteria are photoautotrophs. Chemotrophs derive their energy from the reduction of inorganic compounds like Fe(III), Mn(IV), sulphate, and nitrate or the oxidation of hydrogen sulphide, sulphur, ammonia, nitrite ions, hydrogen and ferrous ion.

Therefore, based on the above two categories, an organism can belong to any one of the following four groups (Tortora et al. 2010):

1. **Photoautotrophs:** They include plants, algae and some bacteria. They use carbon dioxide as their source of carbon and light as their source of energy. These organisms may be pigmented or non-pigmented, and they may be oxygenic or anoxygenic. Green and purple bacteria are well-known examples of photoautotrophs.
2. **Chemoautotrophs:** They include only a few species of bacteria. They use carbon dioxide as the carbon source and energy is obtained from oxidation of inorganic compounds (hydrogen sulphide, sulphur, ammonia, nitrite ions, hydrogen, and ferrous ions). Nitrifying bacteria in wastewater treatment are the best known examples of chemo- or lithoautotrophs.
3. **Photoheterotrophs:** They include a small group of bacteria. They use simple organic compounds such as alcohols, fatty acids, organic acids and carbohydrates as their carbon and light as their energy source. Green and purple non-sulfur bacteria are examples of photoheterotrophs.
4. **Chemoheterotrophs:** They include protozoa, fungi, animals and most bacteria. They utilize organic compounds as their carbon source and obtain energy from oxidation-reduction of organic compounds.

Heterotrophs are of three types based on their nutritional methods:

1. **Saprophytes:** They live off dead organic matter and obtain nutrients through absorption. The best examples are fungi like *Mucor* and *Rhizobium*.
2. **Holozoic:** They ingest solid food or entire particles or other organisms, e.g., *Amoeba*.
3. **Parasites:** They obtain their nutrients from a living host, e.g., all disease-causing organisms or pathogens can be categorized as parasites.

Oxygen may or may not be required for metabolism. Based on its oxygen requirements, an organism is classified as aerobic or anaerobic. Aerobes require oxygen for metabolic activity. Those which undergo metabolic activity in the absence of oxygen are called anaerobes.

3.2 Metabolic Pathways

Chemotrophic organisms (such as those found in SW treatment processes can be autotrophic or heterotrophic) obtain their energy and C by following any of the metabolic pathways listed below. Each of these pathways is a series of oxidation-reduction reactions through which electrons are transported from an electron donor (ED) to a terminal electron acceptor (TEA) whilst generating ATP in the process.

- Aerobic respiration
- Anaerobic respiration and
- Fermentation

Each of these three pathways is summarized here in terms of the terminal electron acceptor (TEA), ATP yield for glucose and mode of ATP generation. Complete or partial oxidation (no reduction) of organic compounds occurs only in the respiration pathways while the same organic compound is partially oxidized and partially reduced by fermentation.

Aerobic Respiration

- TEA: molecular oxygen
- ATP yield/glucose molecule = 38 (highest possible yield)
- Mode of ATP generation: substrate and oxidative phosphorylation

Anaerobic Respiration

- TEA: inorganic compounds except O_2; examples are nitrate, sulfate, carbonates, Fe(III), and Mn(IV)
- ATP yield/glucose molecule = >2 to <38 (yield depends on TEA and ED)
- Mode of ATP generation: substrate and oxidative phosphorylation

Fermentation

- TEA: same organic compound can serve as both electron donor and TEA
- ATP yield/glucose molecule = 2
- Mode of ATP generation: substrate phosphorylation
- For example, glucose is converted to ethanol (reduced) + CO_2 (oxidized)

Examples of oxidation–reduction reactions for acetate with different TEAs are provided in ‘Basic concepts from biochemistry’ (Sawyer et al. 2000).

3.3 Environmental Conditions

Various environmental factors or conditions can affect the extent and rates of growth of microbes. Major factors are discussed here. In general, there are three cardinal points for every growth or environmental factor (Fig. 15.3)

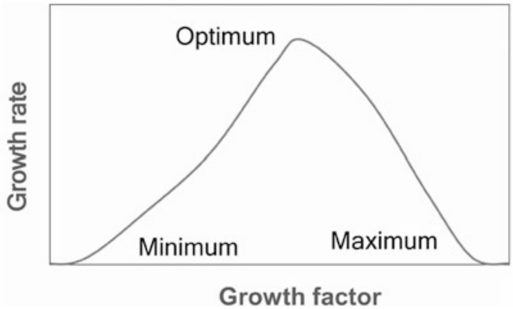


Fig. 15.3 Microbial growth rate in response to changes in specific growth or environmental factors

- Minimum level or concentration at which no growth occurs
- Maximum level or concentration at which no growth occurs and
- Optimum level or concentration for any environmental factor at which microbial growth rates are highest.

3.3.1 Osmotic Effects or Ionic Strength or Water Availability

Microbes contain approximately 70 to 90% water and if placed in a solution with a higher solute concentration, they lose water which causes shrinkage of the cell (plasmolysis). Depending on the water activity, microorganisms are classified into three broad categories:

- Halophiles – Organisms growing optimally at the water activity of seawater (3–3.5% salt or NaCl concentration). Halophiles are subdivided into:
  - mild halophile: 1–6% NaCl (sea water is 3.5% salt)
  - moderate halophile: 6–15% NaCl
  - extreme halophile: 15–30% NaCl
- Osmophiles – organisms living in high sugar environments
- Xerophiles – organisms living in very dry environments

3.3.2 Moisture Content

All microbes need water or moisture to grow. In the absence of moisture, bacteria form endospores which do not reproduce but allow them to survive until moisture and nutrients are available. Similarly, eukaryotes like protozoa form cysts or oocysts to survive in adverse environments (Tortora et al. 2010). Generally, bioprocesses like composting are limited by availability of moisture and therefore, moisture or water needs to be added externally in such cases.

3.3.3 Nutrient Availability

Organisms require both organic as well as inorganic nutrients for creating new biomass. The law of the minimum defines a 'limiting nutrient' and it is important to note that the rate and extent of growth of any organism is limited by the availability of this 'limiting nutrient', also called substrate.

Law of the Minimum
This fundamental principle that applies to the growth of all living organisms was first formulated in agricultural science by Carl Sprengel in 1828 and later popularized by Justus von Liebig.[1]

Any element that is least available relative to the requirements of an organism is defined as the limiting nutrient since the growth of the organism is directly proportionate to the concentration of the limiting nutrient.

In general, any one of the macronutrients is often considered to be the limiting nutrient in an aquatic system. However, *it is important to note that any element (macro- or micro-nutrient) can be the limiting nutrient for the growth of an organism.*

Besides macro- and micro-nutrients, organisms require various other growth factors for proper growth and development. These growth factors include amino acids, vitamins, etc. and are compounds that cannot be synthesised by the organism and therefore, must be supplied externally.

3.3.4 Temperature

Temperature plays an important role in the growth and development of microbes. Higher temperatures speed up chemical reactions. For this reason, growth rates of microbes tend to increase with increase in temperature but only up to a certain point after which cells begin to die. This is mainly because at very high temperatures, denaturation of proteins (enzymes) and nucleic acids takes place resulting in loss of metabolic capabilities.

Cardinal Temperatures Every organism can be characterized by three temperatures:

- **minimum temperature** below which no growth occurs
- **optimum temperature** at which fastest growth occurs
- **maximum temperature** above which no growth occurs

Depending on the adaptation of microorganisms to different temperatures, they are classified into four categories as noted below:

1. *Psychrophiles:* optimum temperature is typically 15 °C and maximum temperature is 20 °C or lower; they are able to grow at temperatures below 0 °C. Some

---

[1] Wikipedia (2015) https://en.wikipedia.org/wiki/Liebig%27s_law_of_the_minimum

Table 15.4 Presently known upper temperature limits for growth of living organisms

Group	Upper temperature limits
Animals	
Fish and other aquatic vertebrates	38
Insects	45–50
Ostracods (crustaceans)	49–50
Plants	
Vascular plants	45
Mosses	50
Eukaryotic microorganisms	
Protozoa	56
Algae	55–60
Fungi	60–62
Prokaryotes	
Bacteria	
Cyanobacteria	70–74
Anoxygenic phototrophs	70–73
Chemoorganotrophic/chemolithotrophic bacteria	95
Archaea	
Chemoorganotrophic/chemolithotrophic archaea	113

Source: Madigan et al. (2003)

organisms are **psychrotolerant**, i.e., their optimum growth temperature is 20–40 °C, but they can grow at temperatures as low as 0 °C.

2. *Mesophiles:* optimum temperature is 20–45 °C, minimum around 15–20 °C.
3. *Thermophiles:* optimum temperature is 55 °C or higher.
4. *Hyperthermophiles:* optimum temperature is 80 °C or higher (mostly Archaea belong in this group). These are found in hot springs and deep-sea hydrothermal vents.

Presently known upper limits of temperature tolerance for different organisms are shown in Table 15.4.

3.3.5 pH

The range of pH over which an organism grows is defined by *three cardinal points*:

- *Minimum pH* below which the organism cannot grow,
- *Maximum pH* above which the organism cannot grow, and
- *Optimum pH* at which the organism grows best.

Depending on the growth at different pH, microorganisms are classified as:

- *Acidophiles:* optimal acidic pH range of 1–5.5
- *Neutrophiles:* optimal pH range of 5.5–8

- *Alkaliphiles:* optimal pH range of 8.5–11.5
- *Extreme alkaliphiles:* optimum pH range of 10 or greater.

In the preparation and use of culture media, maintenance of optimum pH is required for the growth of a desired organism. Accordingly, buffer solutions should be incorporated to maintain the pH of the medium in response to bacterial waste products that accumulate during growth. Many pathogenic bacteria exhibit a relatively narrow range of pH over which they grow. Most diagnostic media for the growth and identification of human pathogens have a pH near 7.

It is important to note that most bacteria are neutrophiles (exceptions include some bacteria in acid mine drainage which have an optimum pH of 1–3) and most fungi prefer slight acidic conditions (pH 4–6).

3.3.6 Oxygen

Oxygen is a universal component of cells and is always provided in large amounts by H_2O. However, microorganisms display a wide range of responses to molecular oxygen (O_2). Depending on the requirements of oxygen, organisms are classified into two broad categories.

Aerobes are those organisms that require oxygen for growth. Aerobes are further classified as obligate or facultative.

1. *Obligate aerobes* require O_2 for growth; they use O_2 as their final electron acceptor in aerobic respiration.
2. *Facultative aerobes* (or *facultative anaerobes*) are organisms that can switch between aerobic and anaerobic types of metabolism depending on the availability of oxygen. Under aerobic conditions (presence of O_2) they grow by aerobic respiration, but in the absence of O_2 they switch to fermentation or anaerobic respiration.

Anaerobes do not require oxygen for growth. They are also classified as obligate or facultative.

Obligate Anaerobes (occasionally called *aerophobes*) do not need or use O_2 as a nutrient. In fact, O_2 is a toxic substance for these organisms which either kills or inhibits their growth. Obligate anaerobic prokaryotes may live by fermentation, anaerobic respiration or bacterial photosynthesis, or the process of methanogenesis.

Aerotolerant Anaerobes are bacteria with an exclusively anaerobic (fermentative) type of metabolism but they are insensitive to the presence of O_2. They live by fermentation alone whether or not O_2 is present in their environment.

Microaerophiles These bacteria don't grow at normal atmospheric oxygen (21%), but require small amounts of oxygen for growth (2–10%).

Oxygen conditions for the growth of these microbes are summarized in Table 15.5.

Table 15.5 Terms used to describe the oxygen relationships of microorganisms

Category	Environment		Effect of oxygen
	Aerobic	Anaerobic	
Obligate aerobe	Growth	No growth	Required (utilized for aerobic respiration)
Microaerophile	Growth if O_2 level not too high	No growth	Required but at levels below 0.2 atm
Obligate anaerobe	No growth	Growth	Toxic
Facultative Anaerobe	Growth	Growth	Not required for growth but utilized when available
Aerotolerant Anaerobe	Growth	Growth	Not required and not utilized

4 Microbes in Bioprocessing of Solid Waste

Several bioprocesses have been used for treating solid waste and include composting, vermi-composting, biogas or biofuel generation, and anaerobic digestion. Important microbes or microorganisms that are involved in biological processing of solid waste include the following:

1. **Bacteria:** These are ubiquitous, unicellular prokaryotic microorganisms. They can be autotrophs (phototrophs) or heterotrophs (chemotrophs). Bacteria are tremendously diverse in size, shape, physiology and lifestyle. They are always unicellular (single-celled) with shapes such as cocci (spherical), bacilli (rod-shaped), spirillae or vibrio (comma shaped) as shown in Fig. 15.4. A scanning electron micrograph (SEM) of *Escherichia coli*, a rod-shaped coliform and a common inhabitant of the gastro-intestinal tracts (guts) of warm-blooded animals is shown in Fig. 15.5. It is generally found in the feces of these animals and therefore, is present in soils, water and wastewater and surface runoff.

   Actinomycetes: These microorganisms possess characteristics intermediate between bacteria and fungi. These are generally classified as aerobic, filamentous, Gram-positive bacteria.

2. **Fungi:** These are multicellular, heterotrophic, eukaryotic microorganisms. They grow well in low pH and moisture conditions. Fungi are extensively used in the production of organic acids, antibiotics and enzymes. Decomposition of solid waste in processes such as composting is due primarily to microbes like fungi and bacteria. The best examples of fungi are molds that grow on food and other surfaces in warm and humid environments.

   Yeasts: These are unicellular eukaryotic microorganisms belonging to the kingdom of fungi. Unlike fungi, they cannot form filaments and grow by budding. Cultured strains of yeasts (e.g. *Saccharomyces cerevisiae*) are widely used in the production of alcohols, and fermented products like breads and cakes.

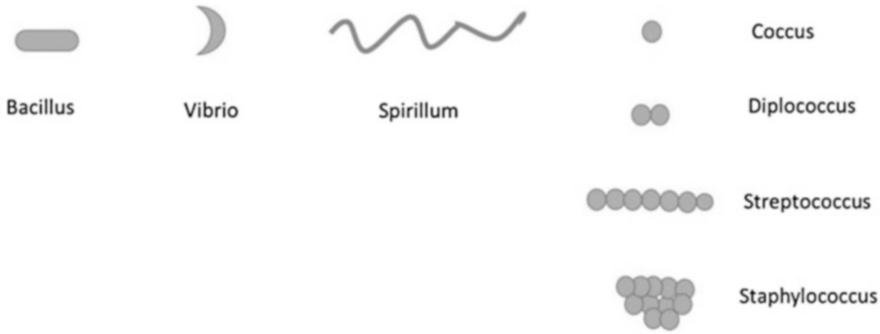


Fig. 15.4 Different shapes of bacteria

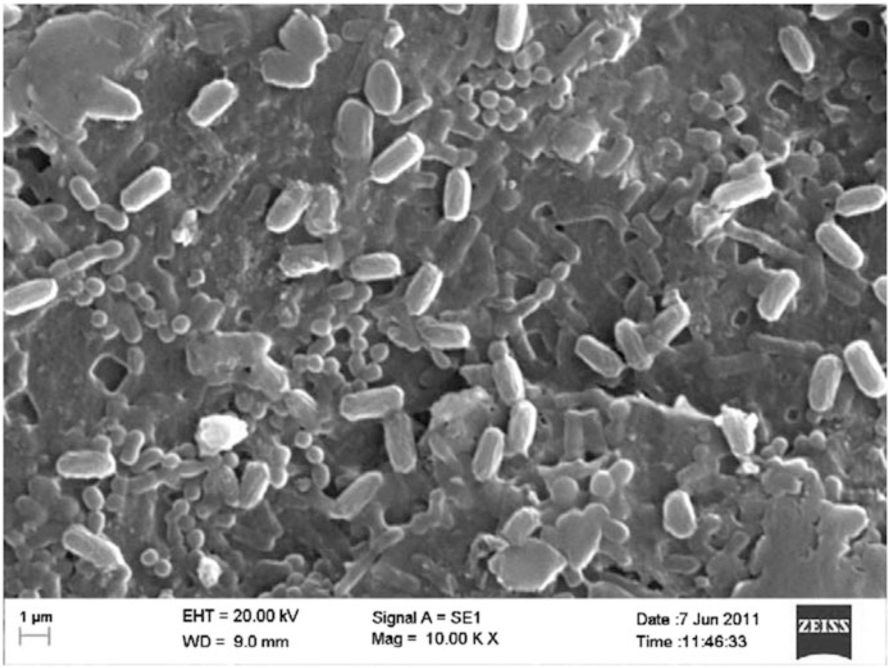


Fig. 15.5 SEM of *Escherichia coli*, a common bacterium (coliform)

5 Bacterial Growth and Its Quantification

Bacterial growth is defined by an increase in cell concentration measured in terms of numbers or cell mass. Growth rate is the change in cell concentration over a period of time, i.e., units of growth are cells/mL-time or g cells/L-time. For bacteria, growth is typically quantified as an increase in cell concentration over unit time. Bacteria reproduce asexually by binary fission in which a bacterial cell

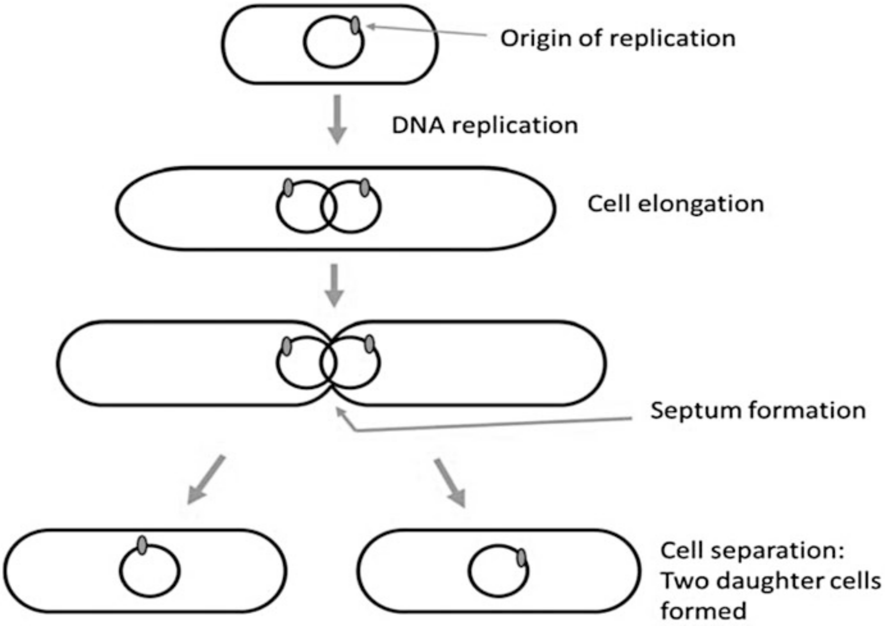


Fig. 15.6 Bacterial reproduction by binary fission

divides and increases its cell number. Figure 15.6 depicts the steps involved in binary fission. A bacterial cell initially increases in size. Its circular chromosome (DNA strand) replicates itself within the large cell, the cell gets elongated and a septum starts forming. Eventually, septum formation is complete resulting in two cells with a single DNA strand in each cell.

5.1 Bacterial Growth Curves in a Batch Culture

Bacterial growth is a result of both, change in cell size and replication of genetic material. Microorganisms can grow under a variety of physical, chemical and nutritional conditions. In a suitable nutrient medium, organisms extract nutrients from the medium and convert them into biomass. Typically, nutrient media are formulated so that a specific nutrient, for example, carbon is the growth limiting nutrient. In other words, all other nutrients are provided in excess of the organism's requirements and only one nutrient serves as the limiting nutrient. This nutrient or substrate is generally monitored in bacterial growth studies.

5.2 Growth Phases

A typical bacterial growth curve in batch culture includes the following phases and is shown in Fig. 15.7. Changes in biomass and substrate concentrations are plotted as a function of time.

1. Lag phase
2. Log phase or exponential phase
3. Stationary phase and
4. Death phase.

1. **Lag phase:** The lag phase occurs immediately after inoculation and is a period of adaptation (or acclimation) of cells to a new environment.

A long lag phase can occur when concentrations of nutrients and/or growth factors are low. For example, when *Enterobacter aerogenes* was grown in glucose and phosphate buffer medium, the lag phase increased with decrease in concentration of Mg^{2+} which is an activator of the enzyme phosphatase (Shuler and Kargi 2001).

2. **Log phase or Exponential phase:** The exponential growth phase is also known as the logarithmic growth phase. During this phase, cell mass and cell number density increase exponentially with time. Metabolic activity increases and the organisms begin replicating their DNA. Eventually, two copies of each cell are created and divide by binary fission. Growth occurs at a constant rate during this phase. The duration of this phase depends on nutrient availability.

During the exponential phase, the net specific growth rate (μ) determined from either cell number-concentration or cell mass is constant. Since the nutrient concentrations are high in this phase, the growth rate is independent of nutrient

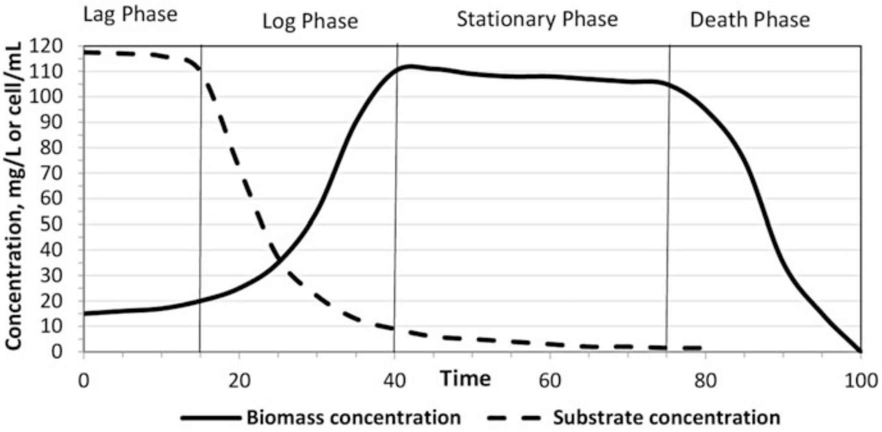


Fig. 15.7 Phases in a bacterial growth curve

concentration. The exponential growth rate is first-order with respect to cell concentration, X.

$$\frac{dX}{dt} = \mu X, \text{where} X = X_0 \,\text{at}\, t = t_0 \tag{15.1}$$

Integration of Eq. (15.1) yields,

$$\ln X/X_0 = \mu\text{t}, \text{or} X = X_0\text{e}^{\mu\text{t}} \tag{15.2}$$

where X and X_0 are cell concentrations at t and $t = 0$.

Exponential growth is characterized by a straight line on a semi-logarithm plot of ln (X/X_0) versus t and the slope of the line is μ for a specific substrate concentration, S.

Doubling time is defined as the time required to double microbial mass and can be determined using Eq. (15.2) by assuming that $X = 2X_0$. The result is Eq. (15.3) given below:

$$\tau_\text{d} = \ln\ 2/\mu = 0.693/\mu \tag{15.3}$$

where τ_d is the doubling time of cell mass.

Similarly, we can calculate a doubling time based on cell numbers and net specific rate of replication (μ_R). Thus, $\tau'_\text{d} = \ln 2/\mu_\text{R}$, where τ'_d is the doubling time based on the replication rate. During balanced growth, τ_d will equal τ'_d, since the average cell composition and size will not change with time.

3. **Stationary phase:** As the bacterial population continues to grow, nutrients in the growth medium are depleted by the microorganisms and the growth rate starts slowing down. At this stage, waste materials and toxic metabolites start accumulating in the medium, pH may decrease as acids accumulate, thereby creating an unfavourable environment for bacterial growth. Eventually the growth rate equals the death rate of cells and there is no net increase in cell concentration. If an inoculum is taken from a stationary phase culture and is introduced into a fresh medium, the culture can easily move to exponential phase.

During the course of the stationary phase, one or more of the following phenomenon may take place:

(a) Biomass concentration may be constant, but the number of viable cells may decrease.
(b) Cell lysis may occur and viable cell numbers may drop. A second growth phase may occur and cells may grow on lysis products of cells.
(c) Cells may not grow but may produce secondary metabolites. Cellular regulation changes when concentrations of certain nutrients like Carbon, Nitrogen and Phosphate are low.

4. **Death or endogenous phase:** The depletion of nutrients and subsequent accumulation of metabolic waste products and other toxic materials in the media will result in a situation where the death rate is greater than the growth rate. During this phase, the bacterial cells start losing their ability to reproduce and often start utilizing their own biomass for survival. The number of dead cells may exceed the number of live cells. Some organisms can resist such conditions and can survive in the environment by producing endospores.

5.3 Monod Kinetics

In the 1930s and 1940s, Jacques Monod performed experiments on bacteria feeding on a single limiting nutrient in order to see if the logistic equation accurately described bacterial growth and published his results in 1949. The Monod model differs from the primary models in the way that it introduces the concept of a growth controlling substrate or limiting nutrient. This model is similar to the Michaelis-Menten model used for describing the kinetics of enzyme reactions (published in 1913). The Monod equation is analogous to Michaelis-Menten kinetics derived in 1913 for a single enzyme system where the amount of an enzyme or its catalytic activity is sufficiently low to make it reaction-rate limiting.

When applied to bacterial cultures, bacterial growth kinetics can be described by the Monod equation:

$$\mu = \mu_{\mathrm{m}} \frac{S}{K_S + S} \quad \text{and} \quad \mu\mathrm{m} = YK \tag{15.4}$$

where S is the concentration of the limiting nutrient or substrate, Y = yield coefficient ($\Delta X/\Delta S$), k = maximum substrate utilization rate per unit mass of cells and μ_{m} is the maximum specific growth rate. A graph corresponding to the above equation is shown in Fig. 15.8 and can be plotted by determining μ values for different S concentrations using Eq. (15.2). The constant K_{s} is known as the saturation constant or half velocity constant and is equal to the concentration of the rate-limiting substrate when the specific rate of growth is equal to one half of the maximum. That is, $K_{\mathrm{s}} = S$ when $\mu = \frac{1}{2}\, \mu_{\mathrm{max}}$. Further, $\mu = \mu_{\mathrm{m}}$ for $S >> K_{\mathrm{s}}$ and $\mu = (\mu_{\mathrm{m}}/K_{\mathrm{s}})S$ for $S << K_{\mathrm{s}}$.

If endogenous decay is included in the growth equation:

$$\mu = \mu_{\mathrm{m}} S/(K_{\mathrm{s}} + S) - k_{\mathrm{d}} = YkS/(K_{\mathrm{s}} + S) \tag{15.5}$$

where k_{d} is the endogenous decay rate.

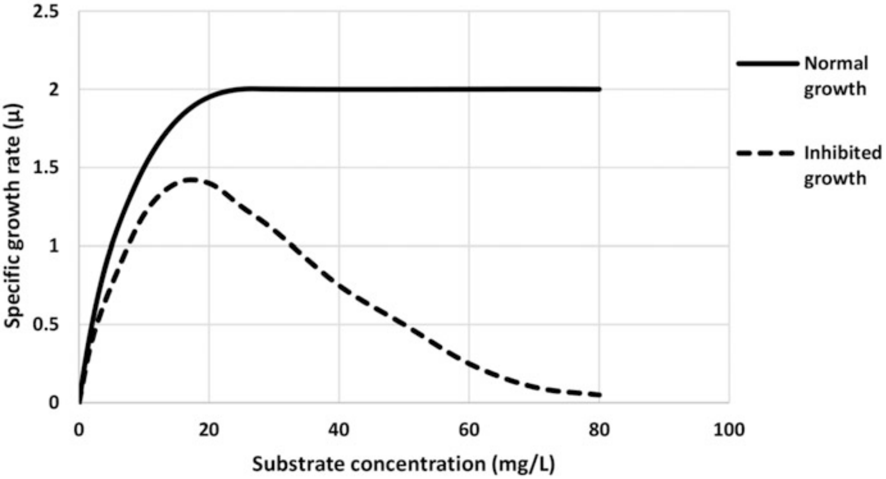


Fig. 15.8 Critical concentration of substrate (S*) under inhibited growth

5.4 *Inhibition and Toxicity*

Toxic contaminants like pesticides, heavy metals and other synthetic organic compounds can inhibit the growth of microbes (LaGrega et al. 2001). As shown in Fig. 15.8, the presence of toxic or inhibitory substances will result in μ_m values that are lower than in the absence of these substances. Further, the onset of the death or endogenous phase will occur at an earlier time due to the presence of inhibitory substances.

The critical concentration of substrate does not follow Monod kinetics due to the presence of toxic substances and the specific growth rate is lower than that without toxic substances. In Fig. 15.8, S* is the concentration at which the maximum specific growth rate occurs.

6 Summary

Microbes are an essential part of many solid waste treatment processes. This chapter provides a simple and brief summary of the fundamentals of microbiology that are essential for understanding and controlling the behaviour of microorganisms in natural or engineered systems.

References

LaGrega, M., Buckingham, P. and Evans, J., 2001. *Hazardous Waste Management*. McGraw Hill International.

Madigan, M.T., Martinko, J.M., Bender, K., Buckley, D. and Stahl, D., 2015. *Brock Biology of Microorganisms* (14th ed.). Pearson Publishers. doi:10.1017/CBO9781107415324.004

Madigan, M.T., Martinko, J.M. and Parker, J., 2003. *Brock Biology of Microorganisms*. Prentice Hall, New Jersey.

Metcalf and Eddy., 2003. *Wastewater Engineering: Treatment, disposal and reuse*. Tata McGraw Hill. New Delhi.

Sawyer, C., McCarty, P. and Parkin, G. 2000. Chemistry for Environmental Engineering and Science. Tata McGraw Hill, New Delhi.

Shuler, M. and Kargi, F., 2001. *Bioprocess Engineering*. Prentice Hall International.

Tortora, G., Funke, B. and Case, C., 2010. *Microbiology: An Introduction*. Benjamin Cummings, USA.

Whittaker, R.H. and Margulis, L. 1978. Protist classification and the kingdoms of organisms. *Biosystems*, **10(1),** 3–18.

Appendix A

USEPA—RCRA's Chemical Waste Compatibility List

The mixing of Group A materials with Group B materials may have the following potential consequences.

Group 1A	Group 1B
Acetylene sludge	Acid sludge
Alkaline caustic liquids	Acid and water
Alkaline cleaner	Battery acid
Alkaline corrosive liquids	Chemical cleaners
Alkaline corrosive battery fluids	Electrolyte, acid
Caustic wastewater	Etching acid liquor or solvents
Lime sludge and other corrosive alkalis	Pickling liquor and other corrosive acids
Lime wastewater	Spent acid
Lime and water	Spent mixed acid
Spent caustic	Spent sulphuric acid
Potential consequences: Heat generation; violent reaction	
Group 2A	**Group 2B**
Aluminum	Any waste in Group 1-A or 1-B
Beryllium	
Calcium	
Lithium	
Magnesium	
Potassium	
Sodium	
Zinc powder	
Other reactive metals and metal hydroxides	
Potential consequences: Fire or explosion; generation of flammable hydrogen gas	

(continued)

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1

Group 3A	Group 3B
Alcohols	Any concentrated waste in Groups 1-A or 1-B
Water	Calcium
	Lithium
	Metal hydrides
	Potassium
	SO_2Cl_2, $SOCl_2$, PCl_3, CH_3SiCl_3
	Other water-reactive waste

Potential consequences: Fire, explosion, or heat generation; generation of flammable or toxic gases

Group 4A	Group 4B
Alcohols	Concentrated Group 1-A or 1-B wastes
Aldehydes	Group 2A wastes
Halogenated hydrocarbons	
Nitrated hydrocarbons	
Unsaturated hydrocarbons	
Other reactive organic compounds and solvents	

Potential consequences: Fire, explosion, or violent reaction

Group 5A	Group 5B
Spent cyanide and sulphide solutions	Group 1-B wastes

Potential consequences: Generation of toxic hydrogen cyanide or hydrogen sulphide gas

Group 6A	Group 6B
Chlorates	Acetic acid and other organic acids
Chlorine	Concentrated mineral acids
Chlorites	Group 2-A wastes
Chromic acid	Group 5-A wastes
Hypochlorites	Other flammable and combustible wastes
Nitrates	
Nitric acid, fuming	
Perchlorates	
Permanganates	
Peroxides	
Other strong oxidizers	

Potential consequences: Fire, explosion, or violent reaction

Appendix B

Environmental Regulations in India

Two terms are used repeatedly in the following section: Act and Rules. These terms are defined in the following table and salient features of all Acts and Rules pertaining to the environment are described after that. A more complete description of how an Act is passed in Parliament or in State legislative assemblies is available on the Internet.[1] The reader should rely only on the full text of each of the Acts and Rules described in Appendix A. The full text can be obtained from http://envfor.nic.in/

Act	Rule
Act means a law	Rules are its procedures
Act means what should be done. It provides the basic framework of the law	Rules are guidelines
The Act contains substantive provisions	Rules specify the procedure for implementing the main provisions of the Act
Act is the statute which prescribes the action by its provisions	Rules flow from the statute to enable its provisions
Act contains main legal provisions on a subject	Rules are mainly procedural matters
Passing an Act is time-consuming	Making Rules takes less time

Water (Prevention and Control of Pollution) Act, 1974

The main objectives of the Water Act are to provide for prevention, control and abatement of water pollution and the maintenance or restoration of the wholesomeness of water by establishing Central and State Pollution Control Boards to monitor and enforce the regulations. It is designed to assess pollution levels and punish

---

Compiled by Tandra Mohanta and Deblina Dutta, IIT Kharagpur, Kharagpur.

[1] https://en.wikipedia.org/wiki/Lawmaking_procedure_in_India

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1

polluters. The Act was enacted in 1974 and amended in 1988. The Water (Prevention and Control of Pollution) Cess Act was enacted in 1977 to provide for the levy and collection of a cess on water consumed by persons operating and carrying on certain types of industrial activities. This cess is collected with a view to augment the resources of the Central Board and the State Boards for the prevention and control of water pollution constituted under the Water (Prevention and Control of Pollution) Act, 1974. The Water (Prevention and Control of Pollution) Cess Act was last amended in 2003.[2]

Salient Features of the Act

- The Act deals with water pollution and presents an integrated approach to tackle the problem. It is an important legislative measure which was enacted to implement the decision taken in the United Nations' Conference on Human Environment held in June 1972 at Stockholm.
- The Water (Prevention and Control of Pollution) Act, 1974 has 64 Sections and has been divided into eight chapters relating to (i) Preliminary, (ii) Central and State Boards for the Prevention and Control of Water Pollution, (iii) Joint Boards, (iv) Powers and Functions of the Boards, (v) Prevention and Control of Water Pollution, (vi) Funds, Accounts and Audit, (vii) Penalties and Procedures, and (viii) Miscellaneous.
- The Act provides for the creation of the Central Pollution Control Board and State Pollution Control Boards for preventing water pollution, power to take water samples and their analysis, discharge of sewage or trade effluents, appeals, revision, minimum and maximum penalties, publication of names of offenders, offences by companies and Government departments, water laboratories, analysis, etc. It authorises the establishment of Joint Boards.
- The Act prohibits every person from knowingly doing certain acts which cause water pollution. Violation is punishable under Section 43 of the Act with imprisonment up to 6 years and with fine. Even municipalities, or municipal corporations, companies, government departments can be prosecuted under Water Act.

Air (Prevention and Control of Pollution) Act, 1981

The Air (Prevention & Control of Pollution) Act was enacted by the Parliament in 1981 and amended in 1987. The objective of this Act is to prevent, control and abate air pollution. It states that sources of air pollution such as industry, vehicles, power plants, etc., are not permitted to release particulate matter, lead, carbon monoxide, sulphur dioxide, nitrogen oxide, volatile organic compounds (VOCs) or other toxic substances beyond a prescribed level. The Act specifically empowers State

---

[2] http://envfor.nic.in/division/water-pollution

Governments to designate air pollution control areas and to prescribe the type of fuel to be used in these designated areas. According to this Act, no person can operate certain types of industries including asbestos, cement, fertilizer and petroleum industries without consent of the State Board.

The main objectives of the Act are:

(a) To provide for the prevention, control and abatement of air pollution.
(b) To confer on Central and State Pollution Control Boards the powers to implement the provisions of the Act and assign to the Boards functions relating to pollution.

Environment Protection Act, 1986

The Environment Protection Act was enacted in 1986 with the objective of providing protection and improvement of the environment. The Act was last amended in 1991. It empowers the Central Government to establish authorities [under section 3(3)] charged with the mandate of preventing environmental pollution in all its forms and to tackle specific environmental problems that are peculiar to different parts of the country.

According to section 2(a) of Environmental Protection Act (1986), 'Environment' includes (i) water, air and land, and (ii) the interrelationship which exists among and between (a) water, air and land and (b) human beings, other living creatures, plants, micro-organisms and property.

Hazardous Waste (Management, Handling and Transboundary Movement) Rules, 2008

Hazardous Waste Management Rules are notified to ensure safe handling, generation, processing, treatment, packaging, storage, transportation, use, reprocessing, collection, conversion, and offering hazardous waste for sale, destruction and disposal. These Rules came into effect in the year 1989 and have been amended in the years 2000 and 2003. The current notification of the Hazardous Waste (Management, Handling and Transboundary Movement) Rules, 2008 supersedes former notifications. The Rules lay down corresponding duties of various authorities such as MoEF, CPCB, State/UT Govts., SPCBs/PCCs, DGFT, Port Authority and Custom Authority while State Pollution Control Boards/Pollution Control Committees have been designated with wider responsibilities touching almost every aspect of hazardous wastes generation, handling and their disposal.

Hazardous waste means any waste which by reason of any of its physical, chemical, reactive, toxic, flammable, explosive or corrosive characteristics causes danger or is likely to cause danger to health or environment, whether alone or when in contact with other wastes or substances.

These Rules do not apply to the following categories of waste which are also hazardous but are regulated under a different set of rules and regulations:

(a) Wastewater and exhaust gases as covered under the provisions of the Water (Prevention and Control of Pollution) Act, 1974 (6 of 1974) and the Air (Prevention and Control of Pollution) Act, 1981 (14 of 1981) and rules made thereunder [Regulatory body is the State Pollution Control Board];
(b) Wastes arising out of the operation from ships beyond five kilometres as covered under the provisions of the Merchant Shipping Act, 1958 (44 of 1958) and the rules made thereunder [Regulatory body is the Director General of Shipping, Government of India];
(c) Radioactive wastes as covered under the provisions of the Atomic Energy Act, 1962 (33 of 1962) and rules made thereunder [Regulatory body is the Dept. of Atomic Energy, Government of India (under direct charge of Prime Minister)];
(d) Bio-medical wastes covered under the Bio-Medical Wastes (Management and Handling) Rules, 1998 made under the Act [Regulatory body is the State Pollution Control Board];
(e) Wastes covered under the Municipal Solid Wastes (Management and Handling) Rules, 2000 made under the Act [Regulatory body is the State Pollution Control Board]; and
(f) Lead acid batteries covered under the Batteries (Management and Handling) Rules, 2001 made under the Act [Regulatory body is the State Pollution Control Board].

Fly Ash Rules, 1999[3]

S.O. 1396(E)—Whereas by notification number S.O. 763(E) dated the 14th September, 1999 (hereinafter referred to as the said notification), notification S.O. 979(5) dated the 27th August, 2003 and S.O. 2804 (E) dated the 3rd November; 2009, the Central Government issued directions for restricting the excavation of top soil for manufacture of bricks and promoting utilisation of fly ash in the manufacture of building materials and in construction activities with a specified radius of 100 kilometres from coal or lignite based thermal power plants;

And whereas, vide the said amendment notification number S.O. 804(E) dated the 3rd November, 2009, timeline to achieve the target of 100% utilisation of fly ash by thermal power plants was specified;

And whereas, it is observed that the thermal power plants are yet to achieve the target of 100% utilization of fly ash and the unutilised fly ash quantum is continuously increasing;

And whereas, it is observed that the construction agencies are not using fly ash and fly ash based-products in their construction projects;

And whereas, it is felt that there is an urgent need to provide additional measures for utilization of fly ash and fly ash based products in the country;

---

[3] Emphasis in bold is by the editor

And whereas, the issue has been examined by the Government of India in the Ministry of Environment and Forests and the Central Government is of the opinion that the said notification needs to be amended;

And whereas, clause (a) of sub-rule (3) of rule 5 of the Environment (Protection) Rules, 1986 provides that whenever the Central Government considers it expedient to impose prohibition or restrictions on the locations of any industry or the carrying on of processes or operations in any area, it may give notice of its intention to do so.

Draft Amendments

(1A) Every construction agency engaged in the construction of buildings within a radius of **500 kms (by road)** from a coal or lignite-based thermal power plant shall use only fly ash based products for construction, such as: cement/concrete, fly ash bricks or blocks or tiles or clay fly ash bricks, blocks or tiles or cement fly ash bricks or bricks or blocks or similar products or a combination or aggregate of them in every construction project.

(1B) The provisions of sub-paragraph (1A) shall be applicable to all construction agencies of Central or State or Local Government and private or public sector. It shall be the responsibility of the agencies either undertaking construction or approving the design or both to ensure compliance of the provisions of sub-paragraph (1A) and to submit annual returns to the concerned State Pollution Control Board or Pollution Control Committee.

(1C) Minimum fly ash content for building materials or products to qualify as "fly ash based products" category shall be as given in the table below:

S. No. (1)	**Building materials or products (2)**	**Minimum % of fly ash by weight (3)**
1.	Fly ash bricks, blocks, tiles, etc. made with fly ash, lime, gypsum, sand, stone dust, cement, etc. (without clay).	50% of total raw material.
2.	Paving blocks, paving tiles, checker tiles, mosaic tiles, roofing sheets, pre-cast elements, etc. wherein cement is used as binder.	Usage of PPC (fly ash) or 15% of OPC content.
3.	Cement.	15% of total raw materials.
4.	Clay based building materials such as bricks, blocks, tiles, etc.	25% of total raw materials.
5.	Concrete, mortar and plaster.	Usage of PPC (fly ash) or 15% of total raw material.

(2) The authority for ensuring the use of specified quantity of fly ash as per para (1C) above shall be the concerned Regional Officer of the State Pollution Control Board or the Pollution Control Committee as the case may be. In case of non-compliance, the said authority, in addition to cancellation of consent order issued to establish the brick kiln, shall move the district administration for cancellation of mining lease. The cancellation of mining lease shall be decided after due hearing. To enable the said authority to verify the actual use of fly ash, the thermal power plant shall maintain month-wise records of fly ash made available to each brick kiln.

(2A) The concerned State Government or Union territory Government shall be the enforcing and monitoring authority for ensuring compliance of the provisions of sub-paragraph (1A) and (1B).

(3) In case of non-availability of fly ash from thermal power plants in sufficient quantities as certified by the said power plants, within 500 kms of the site, the stipulation under subparagraph (1A) shall be suitably modified (waived or relaxed) by the concerned State Government or Union territory Government level monitoring committee mentioned elsewhere in this notification.

(3A) A decision on the application for manufacture of fly ash bricks, block and tiles and similar other fly ash based products shall be taken within 30 days from the date of receipt of the application by the concerned State Pollution Control Board or Pollution Control Committee.

(4) Each coal or lignite-based thermal power plant shall constitute a dispute settlement committee which shall include the General Manager of the thermal power plant and a representative of the relevant construction and fly ash brick manufacturing Industry Association/Body, as the case may be. Such a Committee shall ensure unhindered loading and transport of fly ash without any undue loss of time. Any unresolved dispute shall be dealt with by the concerned State or Union territory Government level monitoring committee mentioned elsewhere in this notification.

(5) **No agency, person or organization shall within a distance of 500 kms (by road) of a thermal power plant undertake construction or approve design for construction of roads or flyover embankments with top soil.** The guidelines or specifications issued by the Indian Road Congress (IRC) as contained in IRC specification No. SP: 58 of 2001 regarding use of fly ash shall be followed. Any deviation from this direction can only be agreed to on technical reasons if the same is approved by Chief Engineer (Design) or Engineer-in-Chief of the concerned agency or organisation or on production of a certificate of “fly ash not available” from the thermal power plant(s) (TPPs) located within 100 kms of the site of construction. This certificate shall be provided by the TPP within two working days from the date of receipt of a request for fly ash, if fly ash is not available.

(6) Soil required for top or side covers of embankments of roads or flyovers shall be excavated from the embankment site and if it is not possible to do so, only the minimum quantity of soil required for the purpose shall be excavated from soil borrow area. In either case, the topsoil should be kept or stored separately. **Voids created at soil borrow area shall be filled up with fly ash with proper compaction** and covered with topsoil kept separately as above. This would be done as an integral part of embankment project.

(7) No agency, person or organisation shall within a radius of **500 kms** (by road) of a coal or lignite-based thermal power plant undertake or approve or allow reclamation and compaction of low-lying areas with soil. **Only fly ash shall be used for compaction and reclamation.** They shall also ensure that such reclamation and compaction is done in accordance with the specifications and guidelines laid down by the authorities mentioned in sub-paragraph (1) of paragraph 3.

(8) (i) No person or agency shall within 50 kms (by road) from coal or lignite-based thermal power plants, **undertake or approve stowing of mine without using at least 25% of fly ash on weight to weight basis,** of the total stowing materials used

and this shall be done under the guidance of the Director General of Mines Safety (DGMS) or Central Mine Planning and Design Institute Limited (CMPDIL):

Provided that such thermal power stations shall facilitate the availability of required quality and quantity of fly ash as may be decided by the expert committee referred in subparagraph (10) for this purpose.

(ii) No person or agency shall within 50 kms (by road) from coal or lignite-based thermal power plants, **undertake or approve without using at least 20% of fly ash on volume to volume basis of the total materials used for external dump of overburden and same percentage in upper benches of back filling of opencast mines** and this shall be done under the guidance of the Director General of Mines Safety (DGMS) or Central Mine Planning and Design Institute Limited (CMPDIL):

Provided that such thermal power stations shall facilitate the availability of required quality and quantity of fly ash as may be decided by the expert committee referred in subparagraph (10) for this purpose.

(9) The provisions contained in clauses (i) and (ii) of sub-paragraph (8) shall be applicable to all mine agencies under Government, public and private sector and to mines of all minerals or metals or items. It shall be the responsibility of agencies either undertaking or approving the backfilling or stowing of mine or both to ensure compliance of provisions contained in clauses (i) and (ii) of sub-paragraph (8) and to submit annual returns to the concerned State Pollution Control Board or Pollution Control Committee and Indian Bureau of Mines (IBM) as applicable.

(10) The Ministry of Coal for this purpose shall constitute an expert committee comprising representatives from Fly Ash Unit, Department of Science and Technology, Ministry of Science and Technology, Director General of Mines Safety (DGMS), Central Mine Planning and Design Institute Limited (CMPDIL), Ministry of Environment and Forests, Ministry of Power, Ministry of Mines and the Central Institute of Mining and Fuel Research (CIMFR), Dhanbad. The Committee shall also guide and advice the back-filling or stowing in accordance with the Provisions contained in sub-paragraphs (8) and (9) above, and specifications and guidelines laid down by the concerned authorities as mentioned in subparagraph (1) of paragraph (3).

(11) The concerned State Government or Union territory Government shall be the enforcing and monitoring authority for ensuring compliance of the provisions of sub-paragraphs (8) and (9).

Responsibilities of Thermal Power Plants

Every coal or lignite based thermal power plant shall take the following steps to ensure the utilisation of fly ash generated by it, namely:

1. All coal or lignite-based thermal power stations would be free to sell fly ash to the user agencies subject to the following conditions, namely:
    (i) The pond ash and mound ash should be made available free of any charge on "as is where is" basis to manufacturers of bricks, blocks or tiles including clay fly ash product manufacturing unit(s), farmers, the Central and the

State road construction agencies, Public Works Department, and to agencies engaged in backfilling or stowing of mines.

(ii) At least 20% of dry ESP fly ash shall be made available free of charge to units manufacturing fly ash or clay-fly ash bricks, blocks and tiles on a priority basis over other users. If the demand from such agencies falls short of 20% of quantity, the balance quantity can be sold or disposed of by the power station as may be possible.

Provided that the fly ash obtained from the thermal power station should be utilized only for the purpose for which it was obtained from the thermal power station or plant failing which no fly ash shall be made available to the defaulting users.

2. All coal and, or lignite-based thermal power stations and, or expansion units in operation before the date of this notification are to achieve the target of fly ash utilization as per the table given below:

S. No. (1)	**Percentage utilization of fly ash (2)**	**Target date (Date of notification is 3 Nov 2009) (3)**
1.	At least 50% of fly ash generation	One year from the date of issue of this notification.
2.	At least 60% of fly ash generation	Two years from the date of issue of this notification.
3.	At least 75% of fly ash generation	Three years from the date of issue of this notification.
4.	At least 90% fly ash generation	Four years from the date of issue of this notification.
5.	100% fly ash generation	Five years from the date of issue of this notification.

The unutilized fly ash in relation to the target during a year, if any, shall be utilized within next 2 years in addition to the targets stipulated for those years. The balance unutilized fly ash accumulated during first 4 years (the difference between the generation and the utilization target) shall be utilized progressively over next 5 years in addition to 100% utilization of current generation of fly ash.

3. New coal and, or lignite-based thermal power stations and, or expansion units commissioned after this notification to achieve the target of fly ash utilization as per table given below:

S. No. (1)	**Percentage utilization of fly ash (2)**	**Target date (3)**
1.	At least 50% of fly ash generation	One year from the date of commissioning.
2.	At least 70% of fly ash generation	Two years from the date of commissioning.
3.	At least 90% of fly ash generation	Three years from the date of commissioning.
4.	100% fly ash generation	Four years from the date of commissioning.

The unutilized fly ash in relation to the target during a year, if any, shall be utilized within next 2 years in addition to the targets stipulated for these years. The unutilized fly ash accumulated during first 3 years (the difference between the generation and utilization target) shall be utilized progressively over next 5 years in addition to 100% utilization of current generation of fly ash.

4. All action plans prepared by coal or lignite-based thermal power plants in accordance with sub-paras (2) and (3) of para (2) of this notification shall be

submitted to the Central Pollution Control Board/Committee and concerned, State Pollution Control Board/Committee and concerned regional office of the Ministry of Environment and Forests within a period of 4 months from the date of publication of this notification.

5. The Central and State Government Agencies, the State Electricity Boards, the National Thermal Power Corporation and the management of the thermal power plants shall facilitate in making available land, electricity and water for manufacturing activities and provide access to the fly ash lifting area for promoting and setting up of ash-based production units in the proximity of the area where fly ash is generated by the power plant.
6. The amount collected from sale of fly ash and fly ash based products by coal and/or lignite-based thermal power stations or their subsidiary or sister concern unit, as applicable should be kept in a separate account head and shall be utilized only for development of infrastructure or facilities and promotion/facilitation activities for use of fly ash until 100% fly ash utilization level is achieved. Thereafter as long as 100% fly ash utilization levels are maintained, the thermal power station would be free to utilize the amount collected for other development programmes also. In case, there is a reduction in the fly ash utilization levels in the subsequent year(s), the use of financial return from fly ash shall get restricted to development of infrastructure or facilities and promotion or facilitation activities for fly ash utilization until 100% fly ash utilization level is again achieved and maintained.
7. Annual implementation report (for the period 1st April to 31st March) providing information about the compliance of provisions in this notification shall be submitted by the 30th day of April, every year to the Central Pollution Control Board, concerned State Pollution Control Board or Committee and the concerned Regional Office of the Ministry of Environment and Forests by the coal or lignite-based thermal power plants, and also be made a part of the annual report of the thermal power plant as well as thermal power plant-wise information be provided in the annual report of thermal power producing agency owning more than one thermal power plant.
8. Every coal or lignite based thermal plants shall (a suitable date prospective to final notification is to be specified) upload the stock of each type of fly ash available with them on their website and, thereafter shall update the stock position for each type of fly ash at least once in every fortnight.
9. Within a radius of 100 kms from a coal or lignite-based thermal power plant, the cost of transportation of fly ash for building and road construction projects shall be borne by such coal or lignite-based thermal power plant and the cost of transportation beyond a radius of 100 kms and upto 500 kms shall be shared equally between the user construction agency engaged and the coal or lignite-based thermal power plant.
10. The coal or lignite-based thermal power plants within a radius of 500 kms shall bear the entire cost of transportation of fly ash to the site of road construction projects under Pradhan Mantri Gramin Sadak Yojna and asset creation programmes of the Government involving construction of buildings, roads, dams and embankments.

Specifications for Use of Fly Ash-Based Products

(1) Manufacture of fly ash-based products such as cement, concrete blocks, bricks, panels or any other material or the use of fly ash in construction activity such as in road laying, embankments or use as landfill to reclaim low lying areas including back filling in abandoned mines or pitheads or for any other use shall be carried out in accordance with specifications and guidelines laid down by the Bureau of Indian Standards, Indian Bureau of Mines, Indian Road Congress, Central Building Research Institute, Roorkee, Central Road Research Institute, New Delhi, Building Materials and Technology Promotion Council, New Delhi, Central Public Works Department, State Public Works Departments and other Central and State Government agencies.

(2) The Central Public Works Department, Public Works Departments in the State/Union Territory Governments, Development Authorities, Housing Boards, National Highway Authority of India and other construction agencies including those in the private sector shall also prescribe the use of fly ash and fly ash-based products in their respective tender documents, schedules of specifications and construction applications including appropriate standards and codes of practice with immediate effect.

(2A) Building construction agencies both in public and private shall prescribe the use of fly ash and fly ash-based products in their respective tender documents, schedules of specifications and construction applications, including appropriate standards and codes of practice and make provisions for the use of fly ash and fly ash based bricks, blocks or tiles or aggregates of them in the schedule of approved materials and rates immediately.

(2B) All agencies undertaking construction of roads or flyover bridges and reclamation and compaction of low lying areas, including Department of Road Transport and Highways (DORTH), National Highways Authority of India (NHAI), Central Public Works Department (CPWD), State Public Works Departments and other State Government Agencies, shall with immediate effect:

(a) make provisions in their tender documents, schedules of approved materials and rates as well as technical documents for implementation of this notification, including those relating to soil borrow area or pit as per sub-paragraph (7) of paragraph 1; and.
(b) make necessary specifications or guidelines for road or flyover embankments that are not covered by the specifications laid down by the Indian Road Congress (IRC).

(3) All local authorities shall specify in their respective tender documents, building bye-laws and regulations, the use of fly ash and fly ash-based products and construction techniques in building materials, roads embankments or for any usage with immediate effect.

(4) The Central Electricity Authority and other approving agencies may permit the land area for emergency ash pond or fly ash storage area up to 40 h for a

500 MW unit, based on 45% ash content coal, or in the same proportion for units in other capacities taking into account the ash content in coal or lignite to be used.

(5) All financial institutions and agencies which fund construction activities shall include a clause in their loan or grant document for compliance of the provisions of this notification.

(6) A monitoring committee shall be constituted by the Central Government with members from Ministry of Coal, Central Pollution Control Board, Central Electricity Authority, Head Fly Ash Unit of Department of Science and Technology and Building Material Technology Promotion Council to monitor the implementation of the provisions of the notification and submit its recommendations or observations at least once in every 6 months to the Secretary, Ministry of Environment and Forests. Concerned Advisor or Joint Secretary in the Ministry of Environment and Forests will be the convener of this committee.

(7) For the purpose of monitoring the implementation of the provisions of the notification the State Governments or Union territory Government shall constitute a monitoring committee within 3 months from the date of issue of this notification under the chairmanship of Secretary, Department of Environment with representatives from Department of Power, Department of Mining, Road and Building Construction Department and State Pollution Control Board. This committee would deal with any unresolved issue by dispute settlement committee as prescribed in sub-paragraph (4) of paragraph (1), in addition to monitoring and facilitating implementation of this notification at the respective State Government or Union territory level. This committee would also be empowered to suitably modify (waive or relax) the stipulation under sub-paragraph (1) in case of non-availability of fly ash in sufficient quantities from thermal power plant as certified by the said power plant. The Committee will meet at least once in every quarter.

(8) It shall be the responsibility of all State Authorities approving various construction projects to ensure that Memorandum of Understanding or any other arrangement for using fly ash or fly ash based products is made between the thermal power plants and the construction agency or contractors.

Recycled Plastics Manufacture and Usage Rules, 1999

Recycled Plastics Manufacture and Usage Rules 1999, published and in effect from 2nd September 1999 were amended on 17 June, 2003. These rules were superseded by Plastic Waste (Management & Handling) Rules, 2011.

Plastic Waste (Management & Handling) Rules, 2011

Salient Features

- Carry bags shall either be in natural shade (colourless), which is without any added pigments or made using only those pigments and colourants which are in conformity with Indian Standard: IS 9833:1981 titled as "List of pigments and colourants for use in plastics in contact with foodstuffs, pharmaceuticals and drinking water", as amended from time to time.
- Recycled plastic or products made of recycled plastic shall not be used for storing, carrying, dispensing or packaging food stuffs.
- Carry bag made of virgin or recycled plastic, shall not be less than 50 microns in thickness.
- Plastic sheet or like, which is not an integral part of multilayered packaging or cover made of plastic sheet used for packaging or wrapping the commodity shall not be less than 50 microns in thickness.
- The manufacturer shall not sell or provide or arrange plastic to be used as raw material to a producer, not having valid registration from the concerned State Pollution Control Boards or Pollution Control Committee.
- Sachets using plastic material shall not be used for storing, packing or selling gutkha, tobacco and pan masala.
- Recycled carry bags shall conform to the Indian Standard: IS 14534:1998 titled as Guidelines for Recycling of Plastics, as amended from time to time.
- Carry bags made from compostable plastics shall conform to the Indian Standard: IS/ISO 17088:2008 titled as Specifications for Compostable Plastics, as amended from time to time.
- Plastic material, in any form, shall not be used in any package for packaging gutkha, pan masala and tobacco in all forms.

Municipal Solid Wastes (Management and Handling) Rules, 2000 (Revised 2016[4])

Application: These rules shall apply to every municipal authority responsible for collection, segregation, storage, transportation, processing and disposal of municipal solid wastes. The revised rules have extended jurisdiction to every urban local body, outgrowths in urban agglomerations, census towns as declared by the Registrar General and Census Commissioner of India, notified areas, notified industrial townships, areas under the control of Indian Railways, airports, airbase, port and harbour, defense establishments, special economic zones, State and Central government organizations, places of pilgrims, religious and historical importance as may be notified by respective state government from time to time and to every

---

[4] http://pib.nic.in/newsite/PrintRelease.aspx?relid=138,591

domestic, institutional, commercial and any other non-residential solid waste generator except industrial waste, hazardous waste, hazardous chemicals, biomedical wastes, e-waste, lead acid batteries and radio-active waste.

Salient Features of the Revised Rules

1. *Duties of Waste Generators*

   - All waste generators shall segregate and store the waste generated by them in three separate streams namely bio-degradable, non-biodegradable and domestic hazardous wastes in suitable bins and handover segregated wastes to authorized rag-pickers or waste collectors.
   - Shall wrap securely the used sanitary waste like diapers, sanitary pads etc., in the pouches provided by the manufacturers or brand owners of these products or in a suitable wrapping material and shall place the same in the bin meant for dry waste/non-biodegradable waste.
   - Shall store separately construction and demolition waste, as and when generated and dispose off as per the Construction and Demolition Waste Management Rules, 2016.
   - Shall store horticulture waste and garden waste generated from his premises separately and dispose off as per the directions of the local authority.
   - Shall not throw, burn or burry the solid waste generated by him, on streets, open public spaces outside his premises or in the drain or water bodies.
   - Shall pay such user fee for solid waste management, as specified in the bye-laws of the local bodies.
   - No person shall organize an event or gathering of more than 100 persons at any unlicensed place without intimating the local authority, at least three working days in advance. Such person or the organizer of such event shall ensure segregation of waste at source and handing over of segregated waste to waste collector or agency as specified by local authority.
   - Every street vendor shall keep suitable containers for storage of waste generated during the course of his activity such as food waste, disposable plates, cups, cans, wrappers, coconut shells, leftover food, vegetables, fruits etc. and shall deposit such waste at waste storage depot or container or vehicle as notified by the local authority.
   - All Resident Welfare and Market Associations, Gated communities and institution with an area >5000 sq. m and all hotels and restaurants shall, within 1 year from the date of notification of these rules and in partnership with the local authority ensure segregation of waste at source by the generators as prescribed in these rules, facilitate collection of segregated waste in separate streams, handover recyclable material to either the authorized waste pickers or the authorized recyclers. The bio-degradable waste shall be processed, treated and disposed off through composting or bio-methanation

within the premises as far as possible. The residual waste shall be given to the waste collectors or agency as directed by the local authority.

2. *Duties of Ministry of Urban Development*

MoUD shall formulate National Policy and Strategy on Solid Waste Management including policy on Waste to Energy, promote research and development, undertake training and capacity building of local bodies, provide technical guidelines and project finance and review periodically the measures taken by the States.

3. *Duties of Department of Fertilisers, Ministry of Chemicals and Fertilizers*

Shall provide market development assistance on city compost and ensure promotion of co-marketing of compost with chemical fertilizers in the ratio of 3–4 bags: 6–7 bags by the fertilizer companies to the extent compost is made available for marketing to the companies.

4. *Duties of Ministry of Agriculture, Government of India*

MoA shall provide flexibility in Fertiliser Control Order for manufacturing and sale of compost, propagate utilisation of compost on farm land, set up laboratories to test quality of compost produced by local authorities or their authorized agencies.

5. *Duties of the Ministry of Power*

MoP shall decide tariff or charges for the power generated from the Waste to Energy plants based on solid waste and ensure compulsory purchase power generated from such Waste to Energy plants by DISCOMs.

6. *Duties of Ministry of New and Renewable Energy Sources*

MNRE shall facilitate infrastructure creation for Waste to Energy plants and provide appropriate subsidy or incentives for such Waste to Energy plants.

7. *Duties of the Secretary–Incharge, Urban Development in the States and Union Territories and Duties of the Secretary–Incharge of Village Panchayats or Rural Development Department in the State and Union Territory*

- The Secretary, State Urban Development Department in the State or Union Territory through the Commissioner or Director of Municipal Administration or Director of Local Bodies shall prepare a state policy on solid waste management within a year.
- Ensure identification and allocation of suitable land for setting up processing and disposal facilities for solid wastes within 1 year and incorporate them in the master plan.
- Ensure that a separate space for segregation, storage, decentralized processing of solid waste is demarcated in the development plan for group housing or commercial, institutional or any other non-residential complex exceeding 200 dwellings or having a plot area exceeding 5000 square metres.

- Ensure that the developers of Special Economic Zone, Industrial Estate, Industrial Park earmark at least 5% of the total area of the plot or minimum five plots/sheds for recovery and recycling facility.
- Notify buffer zone for the solid waste processing and disposal facilities of more than 5 tons per day in consultation with the State Pollution Control Board.
- Start a scheme on registration of waste pickers and waste dealers.

8. *Duties of Central Pollution Control Board*

- The Central Pollution Control Board shall co-ordinate with the State Pollution Control Boards and the Pollution Control Committees for implementation of these rules and adherence to the prescribed standards by local authorities; formulate/review the standards for ground water, ambient air, noise pollution, leachate in respect of all solid waste processing and disposal facilities.
- Review the proposals of state pollution control boards or pollution control committees on use of any new technologies for processing, recycling and treatment of solid waste and prescribe performance standards, emission norms for the same within 6 months.
- Prepare an Annual Report on implementation of these rules on the basis of reports received from State Pollution Control Boards and Committees and submit to the Ministry of Environment, Forest and Climate Change and the report shall also be put in public domain.
- Publish guidelines for maintaining buffer zone restricting any residential, commercial or any other construction activity from the outer boundary of the waste processing and disposal facilities for different sizes of facilities handling more than 5 tons per day of solid waste.
- Publish guidelines, from time to time, on environmental aspects of processing and disposal of solid waste to enable local bodies to comply with the provisions of the rules.
- Provide guidance to States or Union Territories on inter-state movement of waste.

9. *Duties and Responsibilities of local authorities and village Panchayats of census towns and urban agglomerations*

- The local authorities and Panchayats shall prepare a solid waste management plan as per State Policy within 6 months.
- Arrange for door-to-door collection of segregated solid waste; integrate rag pickers/informal waste collectors in solid waste management.
- Frame bye-laws incorporating the provisions of these rules within 1 year, prescribe user fee.
- Direct waste generators not to litter and to segregate the waste at source and handover the segregated waste to authorized waste pickers or the waste collector authorized by the local authority.

- Setup material recovery facilities or secondary storage facilities and provide easy access to waste pickers and recyclers for collection of segregated recyclable waste.
- Establish waste deposition centre/s for domestic hazardous waste and ensure safe storage and transportation of the domestic hazardous waste to the hazardous waste disposal facility or as may be directed by the state pollution control board/committee.
- Direct street sweepers not to burn tree leaves collected from street sweeping and store them separately and handover to the waste collectors or agency authorised by local authority.
- Provide training on solid waste management to waste-pickers and waste collectors.
- Promote setting up of decentralized compost plant or bio-methanation plant at suitable locations in the markets or in the vicinity of markets ensuring hygienic conditions.
- Collect separately waste from sweeping of streets, lanes and by-lanes daily, or on alternate days or twice a week depending on the density of population, commercial activity and local situation.
- Collect horticulture, parks and garden waste separately and process in the parks and gardens, as far as possible.
- Transport segregated biodegradable waste to the processing facilities like compost plant, bio-methanation plant or any such facility. Preference should be given for on-site processing of such waste.
- Transport non-biodegradable waste to the respective processing facility or material recovery facilities (MRF) or secondary storage facility.
- Transport construction and demolition waste as per the provisions of Construction and Demolition Waste Management Rules, 2016.
- Involve communities in waste management and promotion of home composting, bio-gas generation, decentralized processing of waste at community level subject to control of odour and maintenance of hygienic conditions around the facility.
- Phase out the use of chemical fertilizer in 2 years and use compost in all parks, gardens maintained by local authority and wherever possible in other places under its jurisdiction. Incentives may be provided to recycling initiatives by informal waste recycling sector.
- Facilitate construction, operation and maintenance of solid waste processing facilities such as bio-methanation, microbial composting, vermi-composting, anaerobic digestion or any other appropriate processing for bio-stabilization of biodegradable wastes; waste to energy processes including refused derived fuel for combustible fraction of waste or supply as feedstock to solid waste based power plants or cement kilns.
- Make an application for grant of authorization for setting up waste processing, treatment or disposal facility if the volume of waste is exceeding five metric tons per day.

- Prepare and submit annual report before the 30th April of the succeeding year to the Commissioner or Director, Municipal Administration or designated Officer and be sent to the Secretary-in-Charge of State Urban Development Department or village panchayat or rural development department and to the respective State Pollution Control Board or Pollution Control Committee by the 31st May of every year.
- Educate workers including contract workers and supervisors for door-to-door collection of segregated waste and transporting the unmixed waste during primary and secondary transportation to processing or disposal facility.
- Ensure that the operator of a facility provides personal protection equipment including uniform, fluorescent jacket, hand gloves, raincoats, appropriate foot wear and masks to all workers handling solid waste and the same are used by the workforce.
- Ensure that provisions for setting up of centres for collection, segregation and storage of segregated wastes, are incorporated in building plan while granting approval of building plan of a group housing society or market complex.
- Frame bye-laws and prescribe criteria for levying of spot fine for persons who litters or fails to comply with the provisions of these rules and delegate powers to officers or local bodies to levy spot fines as per the bye laws framed.
- Create public awareness on SWM.
- Stop land filling or dumping of mixed waste soon after the timeline as specified in Rule 23 for setting up and operationalization of sanitary landfill is over.
- Allow only the non-usable, non-recyclable, non-biodegradable, non-combustible and non-reactive inert waste and pre-processing rejects and residues from waste processing facilities to go to sanitary landfill.
- Investigate and analyse all old open dumpsites and existing operational dumpsites for their potential of bio-mining and bio-remediation and wheresoever feasible, take necessary actions to bio-mine or bio-remediate the sites.
- In absence of the potential of bio-mining and bio-remediation of dumpsite, it shall be scientifically capped as per landfill capping norms to prevent further damage to the environment.

10. *Duties of District Magistrate or District Collector or Deputy Commissioner*

The District Magistrate or District Collector or Deputy Commissioner shall facilitate identification and allocation of suitable land for setting up solid waste processing and disposal facilities and review the performance of local bodies, at least once in a quarter.

11. *Duties of State Pollution Control Board or Pollution Control Committee*

The State Pollution Control Board or Pollution Control Committee shall enforce these rules in their State; monitor environmental standards; examine the proposal for grant of authorization; regulate Inter-State movement of waste.

12. *Duty of Manufacturers or Brand Owners of Disposable Products and Sanitary Napkins and Diapers.*

- All manufacturers of disposable products such as tin, glass, plastics packaging etc. or brand owners who introduce such products in the market shall provide necessary financial assistance to local authorities for establishment of waste management system.
- All such brand owners who sale or market their products in such packaging material which are non-biodegradable shall put in place a system to collect back the packaging waste generated due to their production.
- Manufacturers or brand owners or marketing companies of sanitary napkins and diapers shall explore the possibility of using all recyclable materials in their products or they shall provide a pouch or wrapper for disposal of each napkin or diapers along with the packet of their sanitary products.
- All such manufacturers, brand owners or marketing companies shall educate the masses for wrapping and disposal of their products.

13. *Duties of the Industrial Units Located within 100 km from the RDF and Waste to Energy Plants based on Solid Waste*

All industrial units using fuel and located within 100 km from a solid waste based RDF plant shall make arrangements within 6 months from the date of notification of these rules to replace at least 5% of their fuel requirement by RDF so produced.

14. *Criteria for Setting up Solid Waste Processing and Treatment Facility*

- The department dealing with the allocation of land will be responsible for providing suitable land for setting up of the solid waste processing and treatment facilities.
- The operator of the facility shall obtain necessary approvals from the State Pollution Control Board or Pollution Control Committee and responsible for safe and environmentally sound operations of the solid waste processing and/or treatment facilities.
- The operator of the solid waste processing and treatment facility shall submit annual report by 30th April to the State Pollution Control Board/ Pollution Committee and local authority.

15. *Criteria and Actions to be Taken for Solid Waste Management in Hilly Areas*

- Construction of landfill on the hill shall be avoided. A transfer station at a suitable enclosed location shall be setup to collect residual waste from the processing facility and inert waste. A suitable land shall be identified in the plain areas down the hill within 25 km for setting up sanitary landfill. The residual waste from the transfer station shall be disposed off at this sanitary landfill.

- In case of non-availability of such land, efforts shall be made to set up regional sanitary landfill for the inert and residual waste.

16. *Criteria for Waste to Energy Process*

- Non-recyclable waste having calorific value of 1500 kcal/kg or more shall not be disposed of on landfills and shall only be utilized for generating energy either or through refuse-derived fuel or by giving away as feed stock for preparing refuse-derived fuel.
- High calorific wastes shall be used for co-processing in cement or thermal power plants.

17. *State Level Advisory Body*

Every department in-charge of local bodies of the concerned State Government or Union Territory administration shall constitute a State Level Advisory Body within 6 months from the date of notification of these rules.

18. *Time Frame for Implementation*

- Necessary infrastructure for implementation of these rules shall be created by the local bodies and other concerned authorities, as the case may be, on their own directly or by engaging agencies within the time frame specified in the rules, and
- Setting up solid waste processing facilities by all local bodies having 100,000 or more population within 2 years, local bodies and census towns below 100,000 population, setting up common or stand-alone sanitary landfills by or for all local bodies having 0.5 million or more population and setting up common or regional sanitary landfills by all local bodies and census towns under 0.5 million population within 3 years, bio-remediation or capping of old and abandoned dumpsites for 5 years.

19. *Specifications for Sanitary Landfills*

- The rules specifies criteria for site selection, development of facilities at the sanitary landfills, specifications for land filling operations and closure on completion of landfilling, pollution prevention, closure and rehabilitation of old dumps, and specify Criteria for special provisions for hilly areas.
- The rules specify standards of processing and treatment of solid waste, composting, treated leachates and incineration.

Monitoring

- The Ministry of Environment, Forest and Climate Change shall be responsible for overall monitoring the implementation of these rules in the country. It shall constitute a Central Monitoring Committee under the chairmanship of Secretary, Ministry of Environment, Forest and Climate Change comprising the Ministry of Urban Development, Ministry of Rural Development, Ministry of Chemicals and Fertilizers, Ministry of Agriculture, Central Pollution Control Board, Three State Pollution Control Boards/Pollution Control Committees, Urban Development Departments of three State Governments, Rural Development Departments from two State Governments, three Urban Local Bodies, two census towns, FICCI, CII and two subject experts.

- This committee shall meet at least once a year to monitor and review the implementation of the rules. The Ministry may co-opt other experts, if needed. The Committee shall be renewed every 3 years.

Battery (Management and Handling) Rules, 2001

Application These rules shall apply to every manufacturer, importer, re-conditioner, assembler, dealer, recycler, auctioneer, consumer and bulk consumer involved in manufacture, processing, sale, purchase and use of batteries or components thereof.

Responsibilities of Manufacturer, Importer, Assembler and Re-Conditioner

1. Ensure that the used batteries are collected back as per the Schedule against new batteries sold excluding those sold to original equipment manufacturer and bulk consumer(s).
2. Ensure that used batteries collected back are of similar type and specifications as that of the new batteries sold.
3. File a half-yearly return of their sales and buy-back to the State Board in Form I latest by 30 June and 30 December of every year.
4. Set up collection centres either individually or jointly at various places for collection of used batteries from consumers or dealers.
5. Ensure that used batteries collected are sent only to the registered recyclers.
6. Ensure that necessary arrangements are made with dealers for safe transportation from collection centres to the premises of registered recyclers.
7. Ensure that no damage to the environment occurs during transportation.
8. Create public awareness through advertisements, publications, posters or by other means with regard to the following
    (a) hazards of lead;
    (b) responsibility of consumers to return their used batteries only to the dealers or deliver at designated collection centres; and
    (c) addresses of dealers and designated collection centres.
9. Use the international recycling sign on the batteries.
10. Buy recycled lead only from registered recyclers.

11. Bring to the notice of the State Board or the Ministry of Environment and Forests any violation by the dealers.

Batteries (Management and Handling) Rules, 2001 Also Mentioned

1. Registration of Importers.
2. Customs clearance of imports of new lead acid batteries.
3. Responsibilities of dealer.
4. Responsibilities of recycler.
5. Procedure for registration/renewal of registration of recyclers.
6. Responsibilities of consumer or bulk consumer.
7. Responsibilities of auctioneer.
8. Prescribed Authority.
9. Duties of Central Pollution Control Board.
10. Computerization of Records and Returns.

E-Waste (Management and Handling) Rules, 2011

Application These rules effective from 01-05-2012 shall apply to every producer, consumer or bulk consumer involved in the manufacture, sale, and purchase and processing of electrical and electronic equipment or components as specified in Schedule-1, collection centre, dismantler and recycler of e-waste.

Two categories of end of the life electrical and electronic equipment namely (i) IT and Telecommunication Equipment and (ii) Consumer Electricals and Electronics such as TVs, Washing Machines, Refrigerators and Air Conditioners are covered under these Rules.

The rule will not apply to lead acid batteries as covered under the Batteries (Management and Handling) Rules, 2001. The rules shall not apply to Micro and Small enterprises as defined in the Micro, Small and Medium Enterprises Development Act, 2006 (27 of 2006) and radio-active wastes as covered under the provisions of the Atomic Energy Act, 1962 (33 of 1962) and rules made thereunder.

Salient Features of the E Waste Rules

- The E-waste Rules place main responsibility of e-waste management on the producers of the electrical and electronic equipment by introducing the concept of “Extended Producer Responsibility (EPR)”.

- EPR means responsibility of any producer of electrical and electronic equipment, for their product beyond manufacturing until environmentally sound management of their end-of-life products.
- Under this EPR, producer is also entrusted with the responsibility to finance and organize a system to meet the costs involved in complying with EPR.

E-Waste (Management and Handling) Rules, 2015

Application These rules shall apply to every manufacturer, producer, consumer, bulk consumer, collection centres, dealers, refurbishers, dismantler and recycler involved in manufacture, sale, transfer, purchase, collection, storage and processing of e-waste or electrical and electronic equipment (EEE) listed in Schedule-1, including their components, consumables and spare parts which make the product operational.

In the E-waste rules of 2011 the role of producers in EPR to be fulfilled was not clarified.

The draft rules have laid down the details of how producers would go about implementing EPR. The producer of e-waste will now have to seek authorization for carrying out EPR and seek authorization from SPCB or CPCB and submit state specific plans. The state specific EPR plans by the producers will be screened by CPCB.

Producer Responsibility Organizations (PROs) are included in the new rules of 2015 in addition to the Extended Producer Responsibility (EPR).

PROs are professional organizations authorized collectively by producers, but sometimes they also act independently or on a public-private partnership basis. PROs can take the responsibility of a group of producers for collection and channelization of e-waste generated from the 'end of life' of their products.

Another new feature that has been incorporated in the new rules is the Deposit Refund Scheme. Under this, a portion of the sale price shall be retained by the producers and be refundable to consumers once the end-of-life products are channelized according to the prescribed methods.

Penalty

Penalty remains the same under these rules. Penalty and punishment for noncompliance are in accordance with section 15 and 16 of the Environment (Protection) Act, 1986 which says that whoever fails to comply with the rules will be punishable with imprisonment for a term which may extend to 5 years or with fine which may extend to Rs. 1 lakh.

The penal provisions are the same as the existing rules of 2011. Stringent penal provisions are a must which can deter erring parties from violating rules.

Construction and Demolition Waste Management Rules, 2016[5]

Application The rules, effective from 29 March, 2016, shall apply to every waste resulting from construction, re-modelling, repair and demolition of any civil structure of individual or organisation or authority who generates construction and demolition waste such as building materials, debris, rubble.

Duties of the Waste Generator

1. Every waste generator shall prima-facie be responsible for collection, segregation of concrete, soil and others and storage of construction and demolition waste generated, as directed or notified by the concerned local authority in consonance with these rules.
2. The generator shall ensure that other waste (such as solid waste) does not get mixed with this waste and is stored and disposed separately.
3. Waste generators who generate more than 20 tons or more in 1 day or 300 tons per project in a month shall segregate the waste into four streams such as concrete, soil, steel, wood and plastics, bricks and mortar and shall submit waste management plan and get appropriate approvals from the local authority before starting construction or demolition or remodelling work and keep the concerned authorities informed regarding the relevant activities from the planning stage to the implementation stage and this should be on project to project basis.
4. Every waste generator shall keep the construction and demolition waste within the premise or get the waste deposited at collection centre so made by the local body or handover it to the authorised processing facilities of construction and demolition waste; and ensure that there is no littering or deposition of construction and demolition waste so as to prevent obstruction to the traffic or the public or drains.
5. Every waste generator shall pay relevant charges for collection, transportation, processing and disposal as notified by the concerned authorities; Waste generators who generate more than 20 tons or more in 1 day or 300 tons per project in a month shall have to pay for the processing and disposal of construction and demolition waste generated by them, apart from the payment for storage, collection and transportation. The rate shall be fixed by the concerned local authority or any other authority designated by the State Government.

---

[5] http://www.moef.gov.in/sites/default/files/C%20&D%20rules%202,016.pdf

Duties of Service Provider and Their Contractors

1. The service providers shall prepare within 6 months from the date of notification of these rules, a comprehensive waste management plan covering segregation, storage, collection, reuse, recycling, transportation and disposal of construction and demolition waste generated within their jurisdiction.
2. The service providers shall remove all construction and demolition waste and clean the area every day, if possible, or depending upon the duration of the work, the quantity and type of waste generated, appropriate storage and collection, a reasonable timeframe shall be worked out in consultation with the concerned local authority.
3. In case the service providers have no logistics support to carry out the work specified in subrules (1) and (2), they shall tie up with the authorised agencies for removal of construction and demolition waste and pay the relevant charges as notified by the local authority.

Duties of Local Authority

1. The local authority shall issue detailed directions with regard to proper management of construction and demolition waste within its jurisdiction in accordance with the provisions of these rules and the local authority shall seek detailed plan or undertaking as applicable, from generator of construction and demolition waste.
2. Chalk out stages, methodology and equipment, material involved in the overall activity and final clean up after completion of the construction and demolition.
3. Seek assistance from concerned authorities for safe disposal of construction and demolition waste contaminated with industrial hazardous or toxic material or nuclear waste if any.
4. Shall make arrangements and place appropriate containers for collection of waste and shall remove at regular intervals or when they are filled, either through own resources or by appointing private operators.
5. Shall get the collected waste transported to appropriate sites for processing and disposal either through own resources or by appointing private operators.
6. Shall give appropriate incentives to generator for salvaging, processing and or recycling preferably in-situ.
7. Shall examine and sanction the waste management plan of the generators within a period of 1 month or from the date of approval of building plan, whichever is earlier from the date of its submission.
8. Shall keep track of the generation of construction and demolition waste within its jurisdiction and establish a data base and update once in a year.
9. Shall device appropriate measures in consultation with expert institutions for management of construction and demolition waste generated including

processing facility and for using the recycled products in the best possible manner.

10. Shall create a sustained system of information, education and communication for construction and demolition waste through collaboration with expert institutions and civil societies and also disseminate through their own website.
11. Shall make provision for giving incentives for use of material made out of construction and demolition waste in the construction activity including in non-structural concrete, paving blocks, lower layers of road pavements, colony and rural roads.

Criteria for Storage, Processing or Recycling Facilities for Construction and Demolition Waste and Application of Construction and Demolition Waste and Its Products

1. The site for storage and processing or recycling facilities for construction and demolition waste shall be selected as per the criteria given in Schedule I;
2. The operator of the facility as specified in sub-rules (1) shall apply in Form I for authorization from State Pollution Control Board or Pollution Control Committee.
3. The operator of the facility shall submit the annual report to the State Pollution Control Board in Form II.
4. Application of materials made from construction and demolition waste in operation of sanitary landfill shall be as per the criteria given in Schedule II.

Duties of State Pollution Control Board or Pollution Control Committee

1. State Pollution Control Board or Pollution Control Committee shall monitor the implementation of these rules by the concerned local bodies and the competent authorities and the annual report shall be sent to the Central Pollution Control Board and the State Government or Union Territory or any other State level nodal agency identified by the State Government or Union Territory administration for generating State level comprehensive data. Such reports shall also contain the comments and suggestions of the State Pollution Control Board or Pollution Control Committee with respect to any comments or changes required.
2. State Pollution Control Board or Pollution Control Committee shall grant authorization to construction and demolition waste processing facility in Form III as specified under these rules after examining the application received in Form I.
3. State Pollution Control Board or Pollution Control Committee shall prepare annual report in Form IV with special emphasis on the implementation status of compliance of these rules and forward report to Central Pollution Control Board before the 31st July for each financial year.

Duties of State Government or Union Territory Administration

1. The Secretary in-charge of development in the State Government or Union territory administration shall prepare their policy document with respect to management of construction and demolition of waste in accordance with the provisions of these rules within 1 year from date of final notification of these rules.
2. The concerned department in the State Government dealing with land shall be responsible for providing suitable sites for setting up of the storage, processing and recycling facilities for construction and demolition waste.
3. The Town and Country Planning Department shall incorporate the site in the approved land use plan so that there is no disturbance to the processing facility on a long term basis.
4. Procurement of materials made from construction and demolition waste shall be made mandatory to a certain percentage (say 10–20%) in municipal and Government contracts subject to strict quality control.

Duties of the Central Pollution Control Board

The Board shall: (1) prepare operational guidelines related to environmental management of construction and demolition waste management.

(2) Analyze and collate the data received from the State Pollution Control Boards or Pollution Control Committee to review these rules from time to time.

(3) Coordinate with all the State Pollution Control Board and Pollution Control Committees for any matter related to development of environmental standards.

(4) Forward annual compliance report to Central Government before the 30th August for each financial year based on reports given by State Pollution Control Boards or Pollution Control Committees.

Duties of Bureau of Indian Standards and Indian Roads Congress

The Bureau of Indian Standards and Indian Roads Congress shall be responsible for preparation of code of practices and standards for use of recycled materials and products of construction and demolition waste in respect of construction activities and the role of Indian Roads Congress shall be specific to the standards and practices pertaining to construction of roads.

Duties of the Central Government

1. The Ministry of Urban Development, and the Ministry of Rural Development, Ministry of Panchayat Raj, shall be responsible for facilitating local bodies in compliance of these rules.
2. The Ministry of Environment, Forest and Climate Change shall be responsible for reviewing implementation of these rules as and when required.

Timeframe for Implementation of the Provisions of These Rules

The timeline for implementation of these rules shall be as specified in Schedule III.

Accident Reporting by the Construction and Demolition Waste Processing Facilities

In case of any accident during construction and demolition waste processing or treatment or disposal facility, the officer in charge of the facility in the local authority or the operator of the facility shall report of the accident in Form V to the local authority. Local body shall review and issue instruction, if any, to the in-charge of the facility.

Biomedical Waste Handling (BWM), 2016

Biomedical Waste (Management & Handling) Rules, 1998 were notified by the Ministry of Environment & Forests (MoEF) under the Environment (Protection) Act, 1986. These Rules apply to all persons who generate, collect, receive, store, transport, treat, dispose or handle biomedical waste in any form. The 'prescribed authority' for enforcement of the provisions of these rules in respect of all the health care facilities located in any State/Union Territory is the respective State Pollution Control Board (SPCB)/Pollution Control Committee (PCC) and in case of healthcare establishments of the Armed Forces under the Ministry of Defence shall be the Director General, Armed Forces Medical Services (DGAFMS). These Rules consist of six schedules and five forms.

The rules were recently revised, effective from their date of publication, March 28, 2016.

Treatment and Disposal

1. Bio-medical waste shall be treated and disposed off in accordance with Schedule I, and in compliance with the standards provided in Schedule-II by the health care facilities and common bio-medical waste treatment facility.
2. Occupier shall hand over segregated waste as per the Schedule-I to common bio-medical waste treatment facility for treatment, processing and final disposal, provided that, the lab and highly infectious bio-medical waste generated shall be pre-treated by equipment like autoclave or microwave.
3. No occupier shall establish on-site treatment and disposal facility, if a service of common bio-medical waste treatment facility is available at a distance of 75 kms.
4. In cases where service of the common bio-medical waste treatment facility is not available, the Occupiers shall set up requisite biomedical waste treatment equipment like incinerator, autoclave or microwave, shredder prior to commencement of its operation, as per the authorisation given by the prescribed authority.
5. Any person including an occupier or operator of a common bio medical waste treatment facility, intending to use new technologies for treatment of bio medical waste other than those listed in Schedule I shall request the Central Government for laying down the standards or operating parameters.
6. On receipt of a request referred to in sub-rule (5), the Central Government may determine the standards and operating parameters for new technology which may be published in Gazette by the Central Government.
7. Every operator of common bio-medical waste treatment facility shall set up requisite biomedical waste treatment equipment like incinerator, autoclave or microwave, shredder and effluent treatment plant as a part of treatment, prior to commencement of its operation.
8. Every occupier shall phase out use of non-chlorinated plastic bags within 2 years from the date of publication of these rules and after 2 years from such publication of these rules, the chlorinated plastic bags shall not be used for storing and transporting of bio-medical waste and the occupier or operator of a common bio-medical waste treatment facility shall not dispose of such plastics by incineration and the bags used for storing and transporting biomedical waste shall be in compliance with the Bureau of Indian Standards. Till the Standards are published, the carry bags shall be as per the Plastic Waste Management Rules, 2011.
9. After ensuring treatment by autoclaving or microwaving followed by mutilation or shredding, whichever is applicable, the recyclables from the treated bio-medical wastes such as plastics and glass shall be given to such recyclers having valid authorisation or registration from the respective prescribed authority.
10. The Occupier or Operator of a common bio-medical waste treatment facility shall maintain a record of recyclable wastes referred to in sub-rule (9) which are

auctioned or sold and the same shall be submitted to the prescribed authority as part of its annual report. The record shall be open for inspection by the prescribed authorities.

11. The handling and disposal of all the mercury waste and lead waste shall be in accordance with the respective rules and regulations.

Segregation, Packaging, Transportation and Storage

1. No untreated bio-medical waste shall be mixed with other wastes.
2. The bio-medical waste shall be segregated into containers or bags at the point of generation in accordance with Schedule I prior to its storage, transportation, treatment and disposal.
3. The containers or bags referred to in sub-rule (2) shall be labelled as specified in Schedule IV.
4. Bar code and global positioning system shall be added by the Occupier and common bio-medical waste treatment facility in 1 year time.
5. The operator of common bio-medical waste treatment facility shall transport the bio-medical waste from the premises of an occupier to any off-site bio-medical waste treatment facility only in the vehicles having label as provided in part 'A' of the Schedule IV along with necessary information as specified in part 'B' of the Schedule IV.
6. The vehicles used for transportation of bio-medical waste shall comply with the conditions if any stipulated by the State Pollution Control Board or Pollution Control Committee in addition to the requirement contained in the Motor Vehicles Act, 1988 (59 of 1988), if any or the rules made thereunder for transportation of such infectious waste.
7. Untreated human anatomical waste, animal anatomical waste, soiled waste and, biotechnology waste shall not be stored beyond a period of 48 h:
    - Provided that in case for any reason it becomes necessary to store such waste beyond such a period, the occupier shall take appropriate measures to ensure that the waste does not adversely affect human health and the environment and inform the prescribed authority along with the reasons for doing so.
8. Microbiology waste and all other clinical laboratory waste shall be pre-treated by sterilisation to Log 6 or disinfection to Log 4, as per the World Health Organisation guidelines before packing and sending to the common bio-medical waste treatment facility.

Schedule I

Part 1

Biomedical wastes categories and their segregation, collection, treatment, processing and disposal options.

Category (1)	Type of waste (2)	Type of bag or container to be used (3)	Treatment and disposal options (4)
Yellow	**(a) Human Anatomical Waste:** Human tissues, organs, body parts and fetus below the viability period (as per the Medical Termination of Pregnancy Act 1971, amended from time to time). **(b) Animal Anatomical Waste:** Experimental animal carcasses, body parts, organs, tissues, including the waste generated from animals used in experiments or testing in veterinary hospitals or colleges or animal houses	Yellow coloured non-chlorinated plastic bags	Incineration or Plasma Pyrolysis or deep burial[a]
	(c) Soiled Waste: Items contaminated with blood, body fluids like dressings, plaster casts, cotton swabs and bags containing residual or discarded blood and blood components.		Incineration or Plasma Pyrolysis or deep burial[a]. In absence of above facilities, autoclaving or microwaving/hydroclaving followed by shredding or mutilation or combination of sterilization and shredding. Treated waste to be sent for energy recovery.
	(d) Expired or Discarded Medicines: Pharmaceutical waste like antibiotics, cytotoxic drugs including all items contaminated with cytotoxic drugs along with glass or plastic ampoules, vials etc.	Yellow coloured non-chlorinated plastic bags or containers	Expired cytotoxic drugs and items contaminated with cytotoxic drugs to be returned back to the manufacturer or supplier for incineration at temperature >1200 °C or to common bio-medical waste treatment facility or hazardous waste treatment, storage and disposal facility for incineration at >1200 °C Or Encapsulation or Plasma Pyrolysis at >1200 °C. All other discarded medicines shall be either sent back to

(continued)

Category (1)	Type of waste (2)	Type of bag or container to be used (3)	Treatment and disposal options (4)
			manufacturer or disposed by incineration.
	(e) Chemical Waste: Chemicals used in production of biological and used or discarded disinfectants.	Yellow coloured containers or non-chlorinated plastic bags	Disposed of by incineration or Plasma Pyrolysis or Encapsulation in hazardous waste treatment, storage and disposal facility.
	(f) Chemical Liquid Waste: Liquid waste generated due to use of chemicals in production of biological and used or discarded disinfectants, Silver X-ray film developing liquid, discarded Formalin, infected secretions, aspirated body fluids, liquid from laboratories and floor washings, cleaning, housekeeping and disinfecting activities etc.	Separate collection system leading to effluent treatment system	After resource recovery, the chemical liquid waste shall be pre-treated before mixing with other wastewater. The combined discharge shall conform to the discharge norms given in Schedule III.
	(g) Discarded linen, mattresses, beddings contaminated with blood or body fluid.	Non-chlorinated yellow plastic bags or suitable packing material	Non-chlorinated chemical disinfection followed by incineration or Plasma Pyrolysis or for energy recovery. In absence of above facilities, shredding or mutilation or combination of sterilization and shredding. Treated waste to be sent for energy recovery or incineration or Plasma Pyrolysis.
	(h) Microbiology, Biotechnology and other clinical laboratory waste: Blood bags, Laboratory cultures, stocks or specimens of microorganisms, live or attenuated vaccines, human and animal cell cultures used in research, industrial laboratories, production of biological, residual toxins, dishes and devices used for cultures.	Autoclave safe plastic bags or containers	Pre-treat to sterilize with non-chlorinated chemicals on-site as per National AIDS Control Organisation or World Health Organisation guidelines thereafter for Incineration.

(continued)

Category (1)	Type of waste (2)	Type of bag or container to be used (3)	Treatment and disposal options (4)
Red	**Contaminated Waste (Recyclable):** Wastes generated from disposable items such as tubing, bottles, intravenous tubes and sets, catheters, urine bags, syringes (without needles and fixed needle syringes) and vacutainers with their needles cut and gloves.	Red coloured non-chlorinated plastic bags or containers	Autoclaving or microwaving/hydroclaving followed by shredding or mutilation or combination of sterilization and shredding. Treated waste to be sent to registered or authorized recyclers or for energy recovery or plastics to diesel or fuel oil or for road making, whichever is possible. Plastic waste should not be sent to landfill sites.
White (Translucent)	**Waste sharps including Metals:** Needles, syringes with fixed needles, needles from needle tip cutter or burner, scalpels, blades, or any other contaminated sharp object that may cause puncture and cuts. This includes both used, discarded and contaminated metal sharps.	Puncture proof, Leak proof, tamper proof containers	Autoclaving or Dry Heat Sterilization followed by shredding or mutilation or encapsulation in metal container or cement concrete; combination of shredding cum autoclaving; and sent for final disposal to iron foundries (having consent to operate from the State Pollution Control Boards or Pollution Control Committees) or sanitary landfill or designated concrete waste sharp pit.
Blue	**(a) Glassware:** Broken or discarded and contaminated glass including medicine vials and ampoules except those contaminated with cytotoxic wastes.	Cardboard boxes with blue coloured marking	Disinfection (by soaking the washed glass waste after cleaning with detergent and Sodium Hypochlorite treatment) or through autoclaving or microwaving or hydroclaving and then sent for recycling.
	(b) Metallic Body Implants	Cardboard boxes with blue coloured marking	

[a] Disposal by deep burial is permitted only in rural or remote areas where there is no access to common biomedical waste treatment facility. This will be carried out with prior approval from the prescribed authority and as per the Standards specified in Schedule-III. The deep burial facility shall be located as per the provisions and guidelines issued by Central Pollution Control Board from time to time.

Part 2

1. All plastic bags shall be as per BIS standards as and when published, till then the prevailing Plastic Waste Management Rules shall be applicable.
2. Chemical treatment using at least 10% Sodium Hypochlorite having 30% residual chlorine for 20 min or any other equivalent chemical reagent that should demonstrate $\text{Log}_{10}4$ reduction efficiency for microorganisms as given in Schedule III.
3. Mutilation or shredding must be to an extent to prevent unauthorized reuse.
4. There will be no chemical pre-treatment before incineration, except for microbiological, lab and highly infectious waste.
5. Incineration ash (ash from incineration of any bio-medical waste) shall be disposed through hazardous waste treatment, storage and disposal facility, if toxic or hazardous constituents are present beyond the prescribed limits as given in the Hazardous Waste (Management, Handling and Transboundary Movement) Rules, 2008 or as revised from time to time.
6. Dead fetus below the viability period (as per the Medical Termination of Pregnancy Act 1971, amended from time to time) can be considered as human anatomical waste. Such waste should be handed over to the operator of common bio-medical waste treatment and disposal facility in yellow bag with a copy of the official Medical Termination of Pregnancy certificate from the Obstetrician or the Medical Superintendent of hospital or healthcare establishment.
7. Cytotoxic drug vials shall not be handed over to unauthorised person under any circumstances. These shall be sent back to the manufactures for necessary disposal at a single point. As a second option, these may be sent for incineration at common bio-medical waste treatment and disposal facility or TSDFs or plasma pyrolysis at temperature $>1200\ ^\circ\text{C}$.
8. Residual or discarded chemical wastes, used or discarded disinfectants and chemical sludge can be disposed at hazardous waste treatment, storage and disposal facility. In such case, the waste should be sent to hazardous waste treatment, storage and disposal facility through operator of common bio-medical waste treatment and disposal facility only.
9. On-site pre-treatment of laboratory waste, microbiological waste, blood samples, blood bags should be disinfected or sterilized as per the Guidelines of World Health Organisation or National AIDS Control Organisation and then given to the common bio-medical waste treatment and disposal facility.
10. Installation of in-house incinerator is not allowed. However in case there is no common biomedical facility nearby, the same may be installed by the occupier after taking authorisation from the State Pollution Control Board.
11. Syringes should be either mutilated or needles should be cut and or stored in tamper proof, leak proof and puncture proof containers for sharps storage. Wherever the occupier is not linked to a disposal facility it shall be the responsibility of the occupier to sterilize and dispose in the manner prescribed.

12. Bio-medical waste generated in households during healthcare activities shall be segregated as per these rules and handed over in separate bags or containers to municipal waste collectors. Urban Local Bodies shall have tie up with the common bio-medical waste treatment and disposal facility to pickup this waste from the Material Recovery Facility (MRF) or from the house hold directly, for final disposal in the manner prescribed in this schedule.

Appendix C

Country-Wise E-Waste Generation Rates (Ordered from Highest to Lowest by kg/Person-year) (Balde et al. 2015)

Rank	Continent	Country	kg/ person-year	Kilo tons/ year	Regulations[a]	Population (in 1000s)
1	Europe	Norway	28.3	146	Yes	5150
2	Europe	Switzerland	26.3	213	Yes	8098
3	Europe	Iceland	26	9	Yes	331
4	Europe	Denmark	24	135	Yes	5610
5	Europe	UK and N Ireland	23.5	1511	Yes	64,271
6	Europe	Netherlands	23.3	394	Yes	16,861
7	Europe	Sweden	22.2	215	Yes	9655
8	Europe	France	22.1	1419	Yes	63,996
9	Americas	USA	22.1	7072	No	3,19,701
10	Europe	Austria	22	188	Yes	8520
11	Europe	Germany	21.6	1769	Yes	81,589
12	Asia	Hong Kong, China	21.5	157	Yes	7296
13	Europe	Finland	21.4	118	Yes	5476
14	Europe	Belgium	21.4	242	Yes	11,260
15	Europe	Luxembourg	21	12	Yes	550
16	Americas	Canada	20.4	725	No	35,538
17	Oceania	Australia	20	468	Yes	23,339
18	Europe	Ireland	19.8	92	Yes	4641
19	Asia	Singapore	19.6	110	No	5595
20	Americas	Bahamas	19.1	7	No	360
21	Oceania	New Zealand	19	86	No	4510
22	Asia	Taiwan	18.6	438	–	23,499
23	Asia	Brunei	18.1	7	No	411
24	Europe	Spain	17.7	817	Yes	45,995
25	Europe	Italy	17.6	1077	Yes	61,156
26	Asia	Japan	17.3	2200	Yes	1,27,061

(continued)

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1

Rank	Continent	Country	kg/ person-year	Kilo tons/ year	Regulations[a]	Population (in 1000s)
27	Asia	UAE	17.2	101	No	5873
28	Asia	Israel	17.2	138	No	8040
29	Asia	Kuwait	17.2	69	No	3999
30	Asia	UAE	17.2	101	No	5873
31	Asia	Qatar	16.3	33	No	1989
32	Asia	Cyprus	16.3	14	Yes	876
33	Europe	Portugal	16.1	171	Yes	10,569
34	Asia	Republic Korea	15.9	804	Yes	50,475
35	Europe	Greece	15.1	171	Yes	11,242
36	Europe	Slovenia	15	31	Yes	2066
37	Europe	Czech	14.8	157	Yes	10,594
38	Europe	Malta	14.6	6	Yes	418
39	Europe	Estonia	14	19	Yes	1340
40	Asia	Oman	14	46	No	3288
41	Americas	Barbados	13.2	4	No	279
42	Asia	Bahrain	12.9	16	No	1198
43	Europe	Hungary	12.6	125	Yes	9922
44	Asia	Saudi Arabia	12.5	379	No	30,254
45	Americas	Antigua & Barbuda	11.6	1	No	88
46	Europe	Slovakia	11.4	62	Yes	5447
47	Europe	Lithuania	11.4	34	Yes	2970
48	Africa	Seychelles	10.9	1	No	94
49	Africa	Equatorial Guinea	10.8	8	No	785
50	Europe	Croatia	10.8	48	Yes	4402
51	Europe	Bulgaria	10.7	77	Yes	7146
52	Europe	Latvia	10.7	22	Yes	2030
53	Americas	Saint Kitts and Nevis	10.1	1	No	60
54	Europe	Poland	10	397	Yes	39,638
55	Americas	Grenada	10	1	No	106
56	Americas	Saint Lucia	9.9	2	No	170
57	Americas	Chile	9.9	176	No	17,711
58	Americas	Dominica	9.7	1	No	71
59	Americas	Saint Vincent& Grenadines	9.7	1	No	110
60	Americas	Uruguay	9.5	32	No	3404
61	Asia	Lebanon	9.4	39	No	4115
62	Africa	Mauritius	9.3	12	No	1309
63	Europe	Romania	9.2	197	Yes	21,266
64	Americas	Trinidad & Tobago	9	12	No	1341
65	Europe	Russia	8.7	1231	No	1,40,955
66	Americas	Suriname	8.5	5	No	560
67	Africa	Libya	8.3	55	No	6649
68	Africa	Botswana	8.3	16	No	1920
69	Americas	Mexico	8.2	958	No	1,17,181
70	Americas	Panama	8.2	31	No	3788
71	Europe	Belarus	7.7	72	No	9293
72	Asia	Kazakhstan	7.7	131	No	17,019

(continued)

Rank	Continent	Country	kg/ person-year	Kilo tons/ year	Regulations[a]	Population (in 1000s)
73	Africa	Gabon	7.6	12	No	1586
74	Americas	Venezuela	7.6	233	No	30,457
75	Asia	Malaysia	7.6	232	No	30,467
76	Americas	Costa Rica	7.5	36	Yes	4770
77	Asia	Iran	7.4	581	No	78,089
78	Europe	Serbia	7.3	56	Yes	7566
79	Europe	Montenegro	7.1	4	Yes	626
80	Americas	Argentina	7	292	No	41,961
81	Americas	Brazil	7	1412	No	2,01,413
82	Africa	South Africa	6.6	346	No	52,433
83	Asia	Turkey	6.5	503	Yes	76,707
84	Americas	Belize	6.5	2	No	355
85	Asia	Thailand	6.4	419	No	64,945
86	Europe	Albania	6.1	20	No	3275
87	Europe	Yugoslav	6.1	13	Yes	2076
88	Americas	Guyana	6.1	5	No	780
89	Asia	Maldives	6.1	2	No	342
90	Europe	Albania	6.1	20	No	3275
91	Americas	Jamaica	5.8	16	No	2774
92	Europe	Ukraine	5.7	258	No	45,000
93	Americas	Dominican Republic	5.4	58	No	10,610
94	Europe	Bosnia & Herzegovinia	5.3	21	Yes	3871
95	Americas	Colombia	5.3	252	Yes	47,711
96	Asia	Azerbaijan	5.1	48	No	9383
97	Africa	Tunisia	5	56	No	11,060
98	Africa	Namibia	5	11	No	2192
99	Africa	Algeria	4.9	183	No	37,597
100	Americas	Paraguay	4.9	34	No	6930
101	Americas	El Salvador	4.8	30	No	6282
102	Americas	Peru	4.7	148	Yes	31,424
103	Americas	Ecuador	4.6	73	Yes	15,699
104	Asia	Armenia	4.6	16	No	3433
105	Asia	Georgia	4.6	21	No	4531
106	Asia	Jordan	4.5	30	No	6694
107	Asia	China	4.4	6033	Yes	13,67,520
108	Africa	Egypt	4.3	373	No	85,833
109	Asia	Sri Lanka	4.2	87	No	20,964
110	Asia	Timor-Leste	4.1	5	No	1172
111	Americas	Bolivia	4	45	Yes	11,246
112	Africa	Swaziland	4	4	No	1106
113	Asia	Turkmenistan	3.9	22	No	5796
114	Africa	Morocco	3.7	121	No	33,179
115	Asia	Bhutan	3.7	3	Yes	746
116	Americas	Guatemala	3.5	55	No	15,870
117	Asia	Iraq	3.1	112	Yes	35,871
118	Africa	Angola	3	65	No	21,444
119	Asia	Indonesia	3	745	No	2,51,490

(continued)

Rank	Continent	Country	kg/ person-year	Kilo tons/ year	Regulations[a]	Population (in 1000s)
120	Africa	Congo	2.5	11	No	4274
121	Africa	Cape Verde	2	1	No	542
122	Europe	Moldova	1.8	6	No	3553
123	Asia	Mongolia	1.8	5	No	2914
124	Americas	Honduras	1.8	16	No	8546
125	Americas	Nicaragua	1.7	11	No	6165
126	Asia	Uzbekistan	1.5	45	No	30,160
127	Asia	Pakistan	1.4	266	No	1,86,279
128	Africa	Ghana	1.4	38	No	26,216
129	Asia	Philippines	1.3	127	No	99,434
130	Asia	Vietnam	1.3	116	Yes	92,571
131	Asia	India	1.3	1641	No	12,55,565
132	Africa	Nigeria	1.3	219	Yes	1,73,938
133	Africa	Djibouti	1.2	1	No	939
134	Africa	Sao Tome and Principe	1.2	0	No	179
135	Africa	Sudan	1.2	43	No	35,276
136	Asia	Kyrgyzstan	1.2	7	No	5700
137	Asia	Yemen	1.2	34	No	27,460
138	Asia	Lao PDR	1.2	8	No	6557
139	Asia	Yemen	1.2	34	No	27,460
140	Africa	Gambia	1.2	2	No	1927
141	Africa	Kenya	1	44	No	44,572
142	Asia	Cambodia	1	16	No	15,561
143	Africa	Uganda	0.9	33	Yes	38,040
144	Africa	Zambia	0.9	13	No	14,617
145	Africa	Cameroon	0.9	21	Yes	22,544
146	Africa	Lesotho	0.9	2	No	1911
147	Africa	Benin	0.9	8	No	9858
148	Africa	Mauritania	0.9	4	No	3804
149	Africa	Senegal	0.9	12	No	13,830
150	Africa	Chad	0.8	9	No	11,284
151	Asia	Tajikistan	0.8	7	No	8302
152	Asia	Bangladesh	0.8	126	No	1,53,257
153	Africa	Côte d’Ivory	0.8	20	No	24,791
154	Africa	Guinea	0.8	9	No	11,403
155	Africa	Togo	0.8	5	No	6587
156	Africa	Comoros	0.7	1	No	724
157	Africa	Mozambique	0.7	16	No	23,365
158	Africa	Rwanda	0.6	6	No	10,865
159	Americas	Haiti	0.6	6	No	10,470
160	Africa	Burkina Faso	0.6	11	No	18,166
161	Africa	Mali	0.6	10	No	17,379
162	Africa	Ethiopia	0.5	43	No	90,982
163	Africa	Tanzania	0.5	26	No	49,047
164	Asia	Nepal	0.5	15	No	32,010
165	Africa	Guinea-Bissau	0.5	1	No	1646
166	Asia	Myanmar	0.4	29	No	66,257
167	Africa	Sierra Leone	0.4	2	No	6481

(continued)

Rank	Continent	Country	kg/ person-year	Kilo tons/ year	Regulations[a]	Population (in 1000s)
168	Africa	Eritrea	0.3	2	No	6000
169	Africa	Madagascar	0.3	6	No	23,537
170	Africa	Zimbabwe	0.3	4	No	13,260
171	Africa	CAR	0.3	1	No	5109
172	Asia	Afghanistan	0.3	9	No	33,967
173	Africa	Burundi	0.2	2	No	9201
174	Africa	Malawi	0.2	4	No	17,604
175	Africa	Dem Congo	0.2	17	No	79,301
176	Africa	Liberia	0.2	1	No	4187
177	Africa	Niger	0.2	4	No	17,116
178	Asia	Syria			No	

[a] Were any national regulations in effect in 2013?

Index

S. Goel (ed.), *Advances in Solid and Hazardous Waste Management*,
DOI 10.1007/978-3-319-57076-1