Handbook of Environmental Engineering 25

Lawrence K. Wang
Mu-Hao Sung Wang
Yung-Tse Hung *Editors*

Solid Waste Engineering and Management

Volume 3

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Handbook of Environmental Engineering 25

Series Editors

Lawrence K. Wang
PhD, Rutgers University, New Brunswick, NJ, USA
MS, University of Rhode Island, Kingston, RI, USA
MSCE, Missouri University of Science and Technology, Rolla, MO, USA
BSCE, National Cheng Kung University, Taiwan, ROC

Mu-Hao Sung Wang
PhD, Rutgers University, New Brunswick, NJ, USA
MS, University of Rhode Island, Kingston, RI, USA
BSCE, National Cheng Kung University, Taiwan, ROC

The past 75 years have seen the emergence of a growing desire worldwide to take positive actions to restore and protect the environment from the degrading effects of all forms of pollution: air, noise, solid waste, and water. The principle intention of the Handbook of Environmental Engineering (HEE) series is to help readers formulate answers to the fundamental questions facing pollution in the modern era, mainly, how serious is pollution and is the technology needed to abate it not only available, but feasible. Cutting-edge and highly practical, HEE offers educators, students, and engineers a strong grounding in the principles of Environmental Engineering, as well as providing effective methods for developing optimal abatement technologies at costs that are fully justified by the degree of abatement achieved. With an emphasis on using the Best Available Technologies, the authors of these volumes present the necessary engineering protocols derived from the fundamental principles of chemistry, physics, and mathematics, making these volumes a must have for environmental pollution researchers.

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Lawrence K. Wang
Mu-Hao Sung Wang • Yung-Tse Hung
Editors

Hamidi Abdul Aziz
Consulting Editior

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Editors
Lawrence K. Wang
Lenox Institute of Water Technology
Latham, NY, USA

Mu-Hao Sung Wang
Lenox Institute of Water Technology
Latham, NY, USA

Yung-Tse Hung
Cleveland State University
Cleveland, OH, USA

Consulting Editor
Hamidi Abdul Aziz
Universiti Sains Malaysia
Pulau, Pinang, Malaysia

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Preface

The past 75 years have seen the emergence of a growing desire worldwide that positive actions be taken to restore and protect the environment from the degrading effects of all forms of pollution—air, water, soil, thermal, radioactive, and noise. Since pollution is a direct or indirect consequence of waste, the seemingly idealistic demand for "zero discharge" can be construed as an unrealistic demand for zero waste. However, as long as waste continues to exist, we can only attempt to abate the subsequent pollution by converting it to a less noxious form. Three major questions usually arise when a particular type of pollution has been identified: (1) How serious are the environmental pollution and natural resources crisis? (2) Is the technology to abate them available? and (3) Do the costs of abatement justify the degree of abatement achieved for environmental protection and resources conservation? This book is one of the volumes of the Handbook of Environmental Engineering series. The principal intention of this series is to help readers formulate answers to the above three questions.

The traditional approach of applying tried-and-true solutions to specific environmental and natural resources problems has been a major contributing factor to the success of environmental engineering and has accounted in large measure for the establishment of a "methodology of pollution control." However, the realization of the ever-increasing complexity and interrelated nature of current environmental problems renders it imperative that intelligent planning of pollution abatement systems be undertaken. Prerequisite to such planning is an understanding of the performance, potential, and limitations of the various methods of environmental protection available for environmental scientists and engineers. In this series of handbooks, we will review at a tutorial level a broad spectrum of engineering systems (natural environment, processes, operations, and methods) currently being utilized, or of potential utility, for pollution abatement, environmental protection, and natural resources conservation. We believe that the unified interdisciplinary approach presented in these handbooks is a logical step in the evolution of environmental engineering.

Treatment of the various engineering systems presented will show how an engineering formulation of the subject flows naturally from the fundamental principles and theories of chemistry, microbiology, physics, and mathematics. This emphasis on fundamental science recognizes that engineering practice has in recent years become more firmly based on scientific principles rather than on its earlier dependency on an empirical accumulation of facts. It is not intended, though, to neglect empiricism where such data lead quickly to the most economical design. Certain engineering systems are not readily amenable to fundamental scientific analysis, and in these instances we have resorted to less science in favor of more art and empiricism.

Since an environmental solid waste engineer must understand science within the context of applications, we first present the development of the scientific basis of a particular subject, followed by exposition of the pertinent design concepts and operations, and detailed explanations of their applications to natural resources conservation or environmental protection. Throughout the series, methods of mathematical modeling, system analysis, practical design, and calculation are illustrated by numerical examples. These examples clearly demonstrate how organized, analytical reasoning leads to the most direct and clear solutions. Wherever possible, pertinent cost data or models have been provided.

Our treatment of solid waste engineering is offered in the belief that the trained engineer should more firmly understand fundamental principles, be more aware of the similarities and/or differences among many of the engineering systems, and exhibit greater flexibility and originality in the definition and innovative solution of environmental system problems. In short, the environmental solid waste engineers should by conviction and practice be more readily adaptable to change and progress.

Coverage of the unusually broad field of environmental science, technology, engineering, and mathematics (STEM) has demanded expertise that could only be provided through multiple authorships. Each author (or group of authors) was permitted to employ, within reasonable limits, the customary personal style in organizing and presenting a particular subject area; consequently, it has been difficult to treat all subject materials in a homogeneous manner. Moreover, owing to limitations of space, some of the authors' favored topics could not be treated in great detail, and many less important topics had to be merely mentioned or commented on briefly. All authors have provided an excellent list of references at the end of each chapter for the benefit of interested readers. As each chapter is meant to be self-contained, some mild repetition among the various texts was unavoidable. In each case, all omissions or repetitions are the responsibility of the editors and not the individual authors. With the current trend toward metrication, the question of using a consistent system of units has been a problem. Wherever possible, the authors have used the British system (fps) along with the metric equivalent (mks, cgs, or SIU) or vice versa. The editors sincerely hope that this redundancy of units' usage will prove to be useful rather than being disruptive to readers.

The goals of the *Handbook of Environmental Engineering* (*HEE*) series are: (1) to cover entire environmental fields, including air and noise pollution control, solid waste processing and resource recovery, physicochemical treatment processes, biological treatment processes, biotechnology, biosolids management, flotation technology, membrane technology, desalination technology, water resources, natural control processes, radioactive waste disposal, hazardous waste management, and thermal pollution control; and (2) to employ a multimedia approach to environmental conservation and protection since air, water, soil, and energy are all interrelated.

This book (*Solid Waste Engineering and Management*, *Volume 3*) and its two sister books (*Solid Waste Engineering and Management*, *Volumes 1* and *2*) of the *Handbook of Environmental Engineering* (*HEE*) series have been designed to serve as a mini-series of solid waste engineering and management textbooks as well as supplemental reference books. We hope and expect they will prove of equally high value to advanced undergraduate and graduate students, to designers of sustainable natural resources systems, and to scientists and researchers. The editors welcome comments from readers in all of these categories. It is our hope that the three solid waste engineering and management books will not only provide information on solid waste and natural resources engineering but also serve as a basis for advanced study or specialized investigation of the theory and analysis of various natural resources systems.

This book, *Solid Waste Engineering and Management*, *Volume 3*, covers the topics on: solid waste management in the tourism industry; rubber tire recycling and disposal; electronic and electrical equipment waste disposal; healthcare waste management; energy recovery from solid waste; composting by black soldier fly; biodrying of municipal solid waste; landfill leachate treatment; health and safety considerations in waste management; and innovative bioreactor landfill and its leachate and landfill gas management.

This book's first sister book, *Solid Waste Engineering and Management*, *Volume 1*, covers the topics on: introduction to solid waste management; legislation for solid waste management; waste transportation and transfer station: characterization and measurement of solid waste; mechanical volume reduction; combustion and incineration; composting processes for disposal of agricultural and municipal solid wastes; sanitary landfill operation and management; solid waste systems planning; practices of solid waste processing and disposal; and landfilling and its environmental impacts.

This book's second sister book, *Solid Waste Engineering and Management*, *Volume 2*, *covers the topics on:* sustainable solid waste management; single waste stream processing and material recovery facility; construction and demolition waste management and disposal; recovery of plastic waste; solid waste and marine litter management; sewage sludge recycling and disposal; restaurant waste recycle and disposal; sanitary landfill types and design; landfill leachate collection and characterization; and landfill aftercare management plan.

The editors are pleased to acknowledge the encouragement and support received from Mr. Aaron Schiller, Executive Editor of Springer Nature Switzerland AG, and his colleagues, during the conceptual stages of this endeavor. We wish to thank the contributing authors for their time and effort and for having patiently borne our reviews and numerous queries and comments. We are very grateful to our respective families for their patience and understanding during some rather trying times.

Latham, NY, USA — Lawrence K. Wang
Latham, NY, USA — Mu-Hao Sung Wang
Cleveland, OH, USA — Yung-Tse Hung
Nibong Tebal, Pulau Pinang, Malaysia — Hamidi Abdul Aziz

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About the Editors

Lawrence K. Wang has served the society as a professor, inventor, chief engineer, chief editor, and public servant (UN, USEPA, New York State) for 50+ years, with experience in entire field of environmental science, technology, engineering, and mathematics (STEM). He is a licensed NY-MA-NJ-PA-OH Professional Engineer, a certified NY-MA-RI Laboratory Director, a licensed MA-NY Water Operator, and an OSHA Instructor. He has special passion and expertise in developing various innovative technologies, educational programs, licensing courses, international projects, academic publications, and humanitarian organizations, all for his dream goal of promoting world peace. He is a retired Acting President/Professor of the Lenox Institute of Water Technology, USA, a Senior Advisor of the United Nations Industrial Development Organization (UNIDO), Austria, and a former professor/visiting professor of Rensselaer Polytechnic Institute, Stevens Institute of Technology, University of Illinois, National Cheng-Kung University, Zhejiang University, and Tongji University. Dr. Wang is the author of 750+ papers and 50+ books and is credited with 29 invention patents. He holds a BSCE degree from National Cheng-Kung University, Taiwan, ROC, a MSCE degree from the University of Missouri, a MS degree from the University of Rhode Island, and a PhD degree from Rutgers University, USA. Currently he is the book series editor of CRC Press, Springer Nature Switzerland, Lenox Institute Press, World Scientific Singapore, and John Wiley. Dr. Wang has been a Delegate of the People to People International Foundation, a Diplomate of the American Academy of Environmental Engineers, a member of ASCE, AIChE, ASPE, WEF, AWWA, CIE, and OCEESA, and an awardee of many US and international engineering and science awards.

Mu-Hao Sung Wang has been an engineer of the New York State Department of Environmental Conservation, an editor of CRC Press, Springer Nature Switzerland, and Lenox Institute Press, and a university professor of the Stevens Institute of Technology, National Cheng-Kung University, and the Lenox Institute of Water Technology. Totally she has been a government official, and an educator in the USA and Taiwan for over 50 years. Dr. Wang is a licensed Professional Engineer and a Diplomate of the American Academy of Environmental Engineers (AAEE). Her publications have been in the areas of water quality, modeling, environmental sustainability, solid and hazardous waste management, NPDES, flotation technology, industrial waste treatment, and analytical methods. Dr. Wang is the author of over 50 publications and an inventor of 14 US and foreign patents. She holds a BSCE degree from National Cheng-Kung University, Taiwan, ROC, a MS degree from the University of Rhode Island, RI, USA, and a PhD degree from Rutgers University, NJ, USA. She is the Co-Series Editor of the *Handbook of Environmental Engineering* series (Springer Nature Switzerland), Coeditor of the *Advances in Industrial and Hazardous Wastes Treatment* series (CRC Press of Taylor & Francis Group), and the Coeditor of the *Environmental Science, Technology, Engineering and Mathematics* series (Lenox Institute Press). She is a member of AWWA, NYWWA, NEWWA, WEF, NEWEA, CIE, and OCEESA.

Yung-Tse Hung has been Professor of Civil Engineering at Cleveland State University, Cleveland, Ohio, USA, since 1981. He is a Fellow of the American Society of Civil Engineers, a licensed Professional Engineer in Ohio and North Dakota, and a Diplomate of American Academy of Environmental Engineers. He has taught at 16 universities in eight countries. His research interests and publications have been involved with biological treatment processes, solid wastes, hazardous waste management, and industrial waste treatment. Dr. Hung is credited with over 470 publications and presentations, 28 books, and 159 book chapters, in water and wastewater treatment. He received his BSCE and MSCE degrees from National Cheng-Kung University, Taiwan, ROC, and his PhD degree from the University of Texas at Austin, USA. He is the Editor-in-Chief of *International Journal of Environmental Pollution Control and Management*, *International Journal of Environmental Engineering*, and *International Journal of Environmental Engineering Science*, and Co-Editor of the *Advances in Industrial and Hazardous Wastes Treatment* series (CRC Press of Taylor & Francis Group), and the *Handbook of Environmental Engineering* series (Springer). Dr. Hung is also the Chief Editor of the *Handbook of*

Environment and Waste Management series (World Scientific Singapore) and the Permanent Executive Director and Ex-President of OCEESA (Overseas Chinese Environmental Engineers and Scientists Association).

Hamidi Abdul Aziz is a Professor in Environmental Engineering in the School of Civil Engineering, Universiti Sains Malaysia. Professor Aziz received his PhD degree in civil engineering (environmental) from the University of Strathclyde in 1992. He is currently the Head of the Solid Waste Management Cluster (SWAM), Universiti Sains Malaysia. He has 29 years of teaching and research experiences in the field of environmental engineering, mainly related to solid waste management and landfill technology, water and wastewater treatment, leachate treatment, bioremediation, pollution control, and environmental impact assessment. To date, he has graduated over 100 PhD and MSc students and has published over 200 ISI papers and a few books and has become an editor and sits on the editorial board of a few international journals. He was awarded the Top Research Scientist of Malaysia by Malaysia Academy of Sciences in 2012. In 2020 he was listed as among the top 2% Scientist in his field in a global list compiled by the prestigious Stanford University from the United States (US) for the year 2019.

Contributors

Irfana Kabir Ahmad, PhD Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan, Malaysia

Zaber Ahmed School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Rosnani Alkarimiah, PhD School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Hamidi Abdul Aziz, PhD School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Solid Waste Management Cluster, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Hassan Basri, PhD Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan, Malaysia

Noor Ezlin Ahmad Basri, PhD Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan, Malaysia

Ahmad Anas Nagoor Gunny, PhD Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Padang Besar, Perlis, Malaysia

Centre of Excellence for Biomass Utilization, Universiti Malaysia Perlis (UniMAP), Arau, Perlis, Malaysia

Herni Abdul Halim School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Mohamad Haziq Mohd Hanif School of Industrial Technology, Universiti Sains Malaysia, Minden, Pulau Pinang, Malaysia

Hadura Abu Hasan, PhD School of Biological Sciences, Universiti Sains Malaysia, Minden, Pulau Pinang, Malaysia

Hasnuri Mat Hassan, PhD School of Biological Sciences, Universiti Sains Malaysia, Minden, Pulau Pinang, Malaysia

Yung-Tse Hung, PhD, PE, DEE, F-ASCE Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, OH, USA

Shahrul Ismail, PhD Faculty of Ocean Engineering, Technology and Informatics, Universiti Terengganu Malaysia, Kuala Nerus, Terengganu, Malaysia

Izan Jaafar, PhD Environmental Science, Faculty of Science and Marine Environment, Universiti Terengganu Malaysia, Kuala Nerus, Terengganu, Malaysia

Nurul'Ain Ab Jalil, PhD Environmental Science Programme, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan, Malaysia

Mohamad Anuar Kamaruddin School of Industrial Technology, Universiti Sains Malaysia, Minden, Pulau Pinang, Malaysia

Muaz Mohd Zaini Makhtar, PhD School of Technology Industry, Universiti Sains Malaysia, USM, Minden, Pulau Pinang, Malaysia

Faris Aiman Norashiddin School of Industrial Technology, Universiti Sains Malaysia, Minden, Pulau Pinang, Malaysia

Fatehah Mohd Omar School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Puganeshwary Palaniandy, PhD School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Abdubaki Mohamed Hussen Shadi School of Industrial Technology, Universiti Sains Malaysia, Minden, Pulau Pinang, Malaysia

Lee Wen Si School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

P. Aarne Vesilind, PhD Department of Civil and Environmental Engineering, Bucknell University, Lewisburg, PA, USA

Lawrence K. Wang, PhD, PE, DEE Lenox Institute of Water Technology, Latham, NY, USA

United Nations Industrial Development Organization, Vienna, Austria

Mu-Hao Sung Wang, PhD, PE, DEE Lenox Institute of Water Technology, Latham, NY, USA

Noor Zaitun Yahaya, PhD Environmental Technology, Faculty of Ocean Engineering, Technology and Informatic, Universiti Terengganu Malaysia, Kuala Nerus, Terengganu, Malaysia

Mohd Suffian Yusoff, PhD School of Civil Engineering, Engineering Campus, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Solid Waste Management Cluster, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Science and Engineering Research Centre, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Mohamed Shahrir Mohamed Zahari, PhD Faculty of Ocean Engineering, Technology and Informatics, Universiti Terengganu Malaysia, Kuala Nerus, Terengganu, Malaysia

Noor Ainee Zainol, PhD Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Padang Besar, Perlis, Malaysia

Water Research and Environmental Sustainability Growth, Centre of Excellence (Wareg), Universiti Malaysia Perlis (UniMAP), Arau, Perlis, Malaysia

Chapter 1
Solid Waste Management in the Tourism Industry

Mohd Suffian Yusoff, Mohamad Anuar Kamaruddin, Mohamad Haziq Mohd Hanif, Faris Aiman Norashiddin, Abdubaki Mohamed Hussen Shadi, Lawrence K. Wang, and Mu-Hao Sung Wang

Abstract Tourism can generate a lot of opportunities and income, but it also has a lot of negative environmental and health consequences. The production of municipal solid waste and wastewater is one of the most significant impacts on the environment, economy, and finances. A variety of waste sources have been identified, and it is important to understand waste generation and its compositions. However, due to climatic conditions, geography, financial constraints, planning challenges, shifting consumption habits, transient population, and seasonal variations in waste quantity and composition, waste management in tourism destinations is particularly difficult. Furthermore, because parties involved in the design, development, and administration of tourist resorts have conflicts of interest, there is sometimes a lack of enthusiasm to implement new ideas and programs. Waste minimization, recycling, mitigation, best practices, and education should be further implemented to enhance sustainability.

Keywords Solid waste · Waste management · Tourism · Municipal solid waste · Green tourism

M. S. Yusoff (✉)
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: suffian@usm.my

M. A. Kamaruddin · M. H. M. Hanif · F. A. Norashiddin · A. M. H. Shadi
School of Industrial Technology, Universiti Sains Malaysia, Minden, Pulau Pinang, Malaysia
e-mail: anuarkamaruddin@usm.my

L. K. Wang · M.-H. S. Wang
Lenox Institute of Water Technology, Latham, NY, USA

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Nomenclature

AHR	Anthropogenic heat release
BW	Biodegradable waste
CO_2	Carbon dioxide
EIA	Environmental Impact Assessment
EMS	Environmental Management System
ERP	Extended producer responsibility
EU	European Union
GDP	Gross domestic product
GIS	Geographic Information System
HASWCC	High-Altitude Solid Waste Collection Centre
IMO	International Maritime Organization
KAP	Knowledge, attitudes, and practices
kg	Kilogram
MBT	Mechanical/biological treatment
MLR	Multiple linear regression
MRF	Material Recovery Facilities
MSW	Municipal solid waste
MT	Mechanical treatment
NBW	Non-biodegradable waste
OECD	Organisation for Economic Co-operation and Development
PPP	Public-private partnerships
RBW	Readily biodegradable waste
SWM	Solid waste management
TECC	Tourism environmental carrying capacity
THF	Tourism heat footprint
TSS	Total suspended solid
TSR	Tall ship races
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific, and Cultural Organization
UNWTO	United Nations World Tourism Organization
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compounds
WFD	Waste Framework Directive

1.1 Introduction

The tourism industry remains a significant indicator for the development of any country by contributing a high revenue and provides social exchange. Employment opportunity increases due to the opening of various hospitality, restaurant, and tourism attraction which seem a booster for the nation's growth. The tourism industry indeed increases the GDP of the country. Tourism is one of the most important industries in the world, and it is a key driver of socioeconomic development in many areas, especially in developing countries with unique cultural, historical, and natural attractions. Tourism's revenue equals or even exceeds that of oil exports, agricultural goods, and automobiles. Tourism has grown to be one of the most important players in international trade, as well as one of the primary sources of income for many developing countries. This expansion is accompanied by increased destination diversification and competition as well as an increase in the number of employees. The statistic in Fig. 1.1 illustrates how tourist arrivals have risen steadily since the end of World War II in 1950 [1]. According to the United Nations World Tourism Organization (UNWTO), there were just 25 million tourists worldwide in 1950. After 68 years, the number of foreign arrivals has risen to 1.4 billion/year. The rate for international tourist arrivals for the first quarter of 2019 has increased by 4% compared to the same quarter of the previous year.

The modes of transportation for travelling also even contributed to the pollution of the environment. Tourism is responsible for about 8% of global carbon emissions, and the classification can be observed in Fig. 1.2 [2, 3]. Various activities add to tourism's carbon footprint, from plane flights and boat trips to souvenirs and hotels. Visitors from high-income countries account for the bulk of this footprint, with Americans topping the list. Tourism's environmental footprint would rise in tandem with the number of people who can afford to visit [3]. The increasing number of transportations via air, road, and sea eventually increased use of fossil-fuel

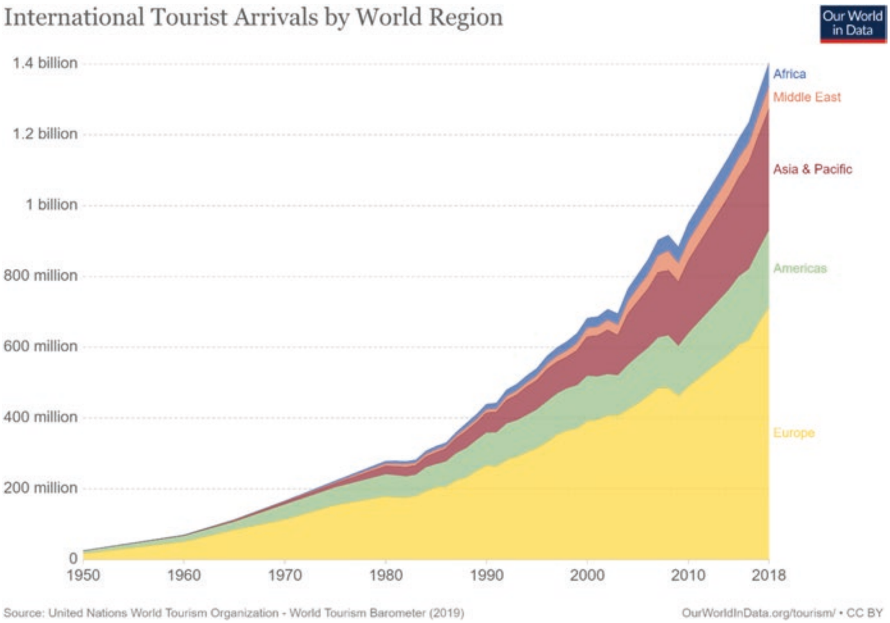

Fig. 1.1 The arrival of tourists by world region. (Source: United Nations World Tourism Organization – World Tourism Barometer (2019). OurWorldInData.org/tourism/, CC BY)

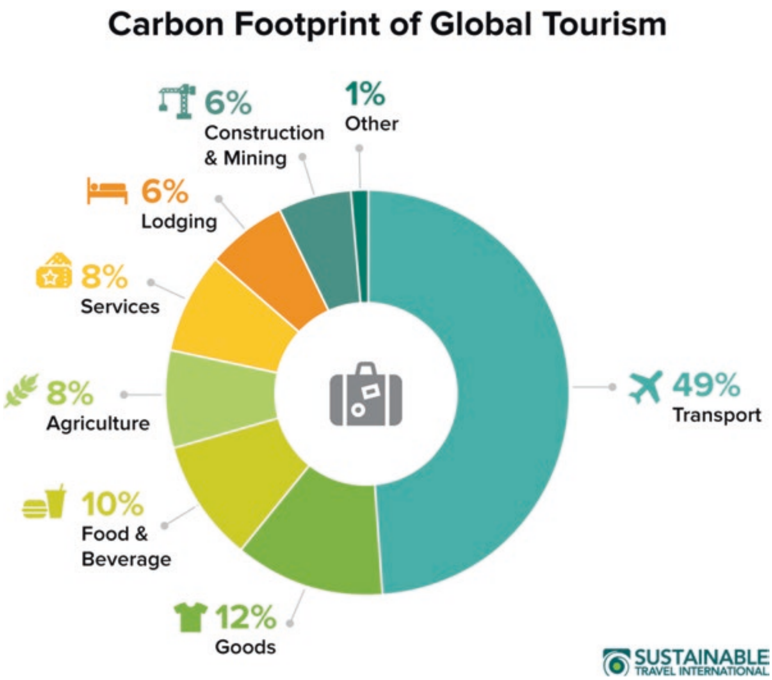

Fig. 1.2 Classification of activities that contribute to tourism's total carbon footprint [2, 3]

vehicles leads to greenhouse gas emissions, persistent organic contaminants, and extreme local air pollution. The debris of sea mode transportation could harm the ecosystem and could end up at the beach if not properly addressed. Planes and cars emit the most CO_2 per passenger mile on average, with tour buses, ferries, and trains trailing far behind. As airfare has become more accessible in recent years, the number of international travellers has increased dramatically. Similarly, transportation-related tourism emissions increased by more than 60% between 2005 and 2016. The average release of carbon dioxide (CO_2) calculated via different modes of transportation is illustrated in Fig. 1.3 [3]. The aircraft industry contributes the most as various trips for domestic and international flights take place. However, with the current outbreaks of Covid 19 pandemics, the aircraft industry is expected to suffer the most as various trips are cancelled and suspended. The carbon footprint for this industry is estimated to drop drastically for at least 2 years period.

1.1.1 Definition of Tourism

The term "tourism" refers to short-term travel outside of one's own country. Tourism is essentially an action or process that involves spending time in a location away from home to recreate, relax, and have fun while utilizing commercial measures,

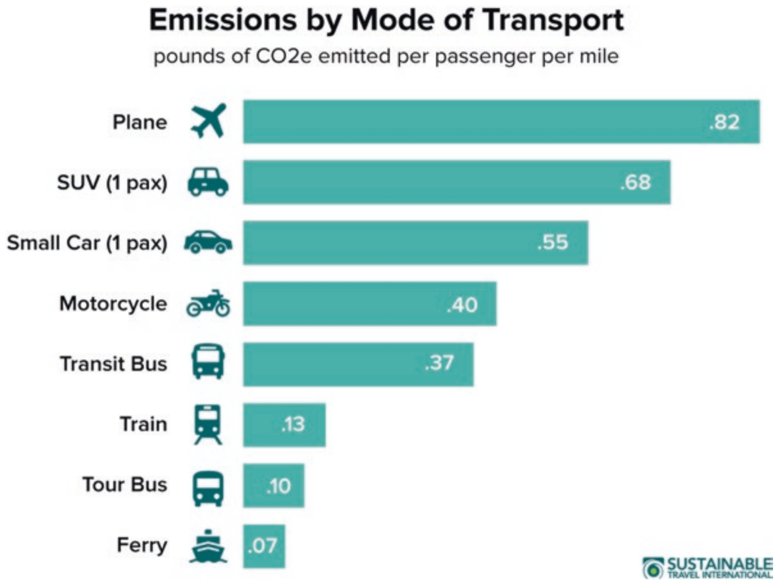

Fig. 1.3 Emission by mode of transport generated in the tourism industry [3]

services, and goods [4]. By 2030, the number of visitors crossing the border is predicted to climb at a pace of 3.3% each year. In nominal terms, there will be 43 million additional visitors each year by 2030, totalling 1.8 billion cross-border excursions [5].

1.1.2 Tourism Waste

Tourism has long been recognized as a high-energy, high-water-resources-demanding operation that also generates large volumes of solid waste from lodgings and leisure activities. Touristic regions' solid waste generation rates can be substantially higher than a municipal solid waste generation, posing severe environmental risks repercussions, especially in low-density populations touristic areas with insufficient facilities to cope with the influx of visitors with waste produced by the indigenous population, which is relatively small [6]. The attitude and the lifestyles of the tourist as well as the operation of tourist facilities contributed to the generation of waste, as described in Fig. 1.4 [7]. According to United Nations Environment Programme (UNEP), the generation of solid waste per person was estimated between 1 and 2 kg for each person per day depending on the locality. Several other types of research have provided data that showed the generation of solid waste could achieve 12 kg/person daily. According to [8], an increase of 1% in the tourist population results in a 0.282% rise in total MSW. Several factors have been identified as the reason for the high generation rate of solid waste. Tourist destinations,

Fig. 1.4 Tourism facility operations and the output [7]

tourist features, the season of the year, and the country's environmental regulations are all factors to consider. Tourists are not aware of how a region's waste management system is meant to function. Tourists are unlikely to stay for long periods because they are only there for a short time and cannot adapt to a particular requirement of the solid waste management system. As several tourist destinations are famous for single seasons, such as winter or summer, they put even more strain on waste management systems due to the mass and volume of solid waste they produce. During the "high season," the number of visitors can also outnumber the amount of waste created by the local community. In most tourism facilities, large amounts of solid waste are produced in guest rooms, kitchens, restaurants, laundries, offices, gardens, and conference rooms, which can have a negative ecological, disease, and aesthetic consequences (if not properly managed). Hotels, guesthouses, restaurants, and golf courses in many destinations face an immediate need to minimize waste, protect the atmosphere, and satisfy an increasing consumer appetite for environmental-friendly facilities.

Various factors contributed to the abundant solid waste generation in tourism waste. Inefficient solid waste management programs, rudimentary or no environmental protection regulations, and weak facilities can exist in certain areas, resulting in major environmental impacts, mostly due to unregulated or substandard solid waste disposal. Without proper regulation, strict law enforcement cannot be carried out, and tourists will take the importance of solid waste management lightly. High operational cost is another reason that inhibits stakeholders and the community from implementing systematic waste management. A proper waste management system provides segregation at the source and recovery of valuable materials that reduces the burden on landfills.

1.1.3 Waste Management

Waste management is often related to the hierarchy of waste as suggested by the United States Environmental Protection Agency (USEPA) in Fig. 1.5 and becoming guidance for other countries. The non-hazardous materials and waste management hierarchy were established by the EPA in appreciation of the fact that no particular waste management solution is appropriate for all materials and waste streams in all situations. The hierarchy lists the different management techniques from the most environmentally friendly to the least environmentally friendly. As part of a sustainable materials management strategy, the hierarchy emphasizes minimizing, reusing, and recycling. The European Union, through the Directive 2008/98/EC of the European Parliament 2008 or known as the Waste Framework Directive (WFD), is an aggressive approach in dealing with solid waste in the European region. All European member states must have structures in place to handle municipal solid waste (MSW) in a sustainable manner, which should include the following elements. (1) Reduction of waste (2) Recycle (3) Recyclability (4) Recovering electricity (5) Disposal in a landfill. The waste hierarchy's objective is to prioritize waste prevention. Prevention is the process of eradicating waste before it is formed. Minimization is the process of reducing waste throughout a product's life cycle. Reuse is the process of repurposing waste materials so that they do not end up in the landfill. Recovery is the process of recovering a portion of the materials' value through recycling and energy recovery. Disposal, which is at the bottom of the

Fig. 1.5 Waste management hierarchy

hierarchy, mainly entails landfilling and waste incineration [9]. Generally, the amount of waste generated per person will be depending on the lifestyle and their affordability which may seem the trends of rich countries producing a massive amount of waste compared to poorer nations. Worldwide municipal solid waste generation is expected to reach 3.4 billion metric tonnes, with the current highest contributor identified from East Asia and the Pacific Regions. Waste management is widely regarded as an expense rather than a revenue-generating capability, especially by the stakeholders.

1.2 Tourism Waste Source

Tourism waste sources are contributed by several players in the tourism industry. Waste cannot be avoided as the demand by the tourists keeps increasing. Tourism players provide enormous attractive offers to expand their products. However, some tourism activities generate a vast amount of waste without proper planning and management, which may affect the environment, economy, and finances if not handled properly.

1.2.1 Resort

The large-scale resort with theme parks, casinos, and water parks have attracted various tourists, either internationally or locally. Vacation at this location can be considered as ideal and a dream vacation as the tourists have many options for their activities. Some resorts may be built near the beach, in the highland, or on an island consuming a large scale of the area with high privileged and privacy for their customers. Commonly, such a resort attracts a high number of tourists, especially during peak season, thus increasing the burden of waste management. With a large area to be covered, the resort ecosystem provides different challenges compared to other management of solid waste. According to Kliopova [10], the author summarizes that the waste management in the resort may differ from others due to several reasons such as the seasonality period for tourists, limited source separation activity, high costs of waste management, and less sense of responsibility by the tourists. One of the examples given by the author regarding waste management is Palanga municipality, the biggest resort center in Lithuania. The author found that only 14% of all waste should be disposed of at the landfill, while approximately 85% of waste is considered biodegradable and can be retrieved as value-added products. Common generator of waste involves the tourists themselves and could be probably generated by the kitchen or catering of the resort. An event that takes place may generate greater waste. The geographical area of the sites influences the modes of management of waste, including transportation and disposal. Due to the inability of proper waste management, some of the tourism providers have taken their approach to manage the waste either legally or illegally. Bhat et al. [11] reported that some resort that faces difficulty in waste management carried out by traditional handcarts collection and dumped illegally nearby the forest for this case. The fragile ecosystem is exposed to massive illegal dumping with no regular supervision.

1.2.2 Hotel/Hospitality

Hotel and hospitality generate various types of waste from different departments and from the tourist. Realizing that the hotel sector is the greatest consumer of durable and non-durable items, it is reasonable to assume that the sector generates a significant quantity of waste [12, 13]. The food and beverage department, for example, generates trash in the form of packaging and food waste, aluminum cans, glass bottles, and cooking oil, while the housekeeping department generates waste in the form of cleaning chemicals and plastic packaging. According to [14], the composition of non-hazardous waste in the hotel industry is listed as shown in Table 1.1. Solid waste, such as packaging materials, kitchen and garden waste, old furniture and appliances, and potentially hazardous wastes, such as asbestos and solvents, are all common in hotels. However, many small hoteliers are uninterested in minimizing and/or recycling waste because they believe it is too expensive and time-consuming [15]. The cost of solid waste for a hotel business comprises not only the

Table 1.1 The composition of non-hazardous waste in the hotel industry

Non-hazardous waste type	Components	Source
Household wastes	Food/kitchen waste, used or dirty paper and wrapping, plastic wrapping or bags, composite wrappers	Hotel's different departments
Cardboard	Packaging	Hotel's different departments
Paper	Printed documents, brochures, menus, maps, magazines, newspaper	Administration, reception, guest rooms, restaurants
Plastic	Bags, bottles (that did not contain hazardous material), household goods, individual portions wrappers for various products	Kitchen, restaurants, bars, guest rooms, administration
Metal	Tin cans, jar lids, soda cans, food containers, mayonnaise, mustard, and tomato puree tubes, aluminum packaging	Kitchen, restaurants, bars, guest rooms
Glass	Bottles, jars, flasks	Kitchen, restaurants, bars, guest rooms
Cloth	Tablecloths, bed linen, napkins, cloths, rags	Kitchen, restaurants, bars, guest rooms, bathrooms
Wood	Wooden packaging, pallets	Purchasing department
Organic waste	Fruit and vegetable peelings, flowers and plants, branches, leaves, and grass	Kitchen, restaurants, bars, guest rooms, gardens

cost of disposal but also other hidden costs such as employees, resources, and energy [16].

According to Matai [17], almost 50% of waste generated from hotel consist of paper and plastic. Newspaper as an example has been a long debate as one of the contributors of waste from hotel/hospitality. Newspapers have already been claimed as one of the major forms of solid waste and dubbed as a real polluter since the previous century [18]. The newspaper can also be described as a silent polluter as they release volatile organic compounds (VOC) from the ink, cleaning solvents, and ozone under exposure to sunlight [19]. Sufficient VOC is enough to harm any human or even create greater damage to the susceptible group. Mitigation or recycling of newspapers is not an easy job as the de-inking process creates waste sludge that needs to be handled and should increase the cost. The de-inking sludge indicated from the process produced around one-half of printed paper [20]. The enormous amount of newspaper distributed by the Three- to Five-star Hotel in 2002 have been summarized in Table 1.2 [19].

1.2.3 Island

The management of solid waste on the island is often linked with a small area for landfill operation and a location that is far away from the mainland. The waste management of the island can be best described as a cradle to grave issue (collection, transportation, treatment, and disposal) that is influenced by several factors. Various challenges are faced by the key player of island tourism, such as seasonal changes in the quantity and composition of waste products, as well as unusual climatic conditions, topography, poor planning, financial constraint, and transient populations [21, 22]. A limited number of waste treatment/disposal facilities and the scarcity of land also contributed to these complex issues. Willmott et al. [22] argue that conventional top-down, regulatory, and end-of-pipe approaches to waste management, especially in island communities, often result in a variety of challenges, including technical issues, a lack of capacity, limited education and knowledge, corruption, stakeholder control, and poor planning. The complex and different priorities by many stakeholders involved in designing and constructing solid waste planning led to poor solid waste management. At some point, island regions are not compulsory to follow the same level of legislative control, such as the mainland states and are required to carry out the best practices that are still reflecting the high standard of legislation [21]. The island that is surrounded by natural ecosystems such as coral reefs, sand beaches, and mangroves ecosystem requires an extensive precaution measure to ensure that the ecosystem is not being harmed.

Shamshiry et al. [23] carried out a study on waste management in Langkawi Island, Malaysia, which consists of Geopark that is still well preserved. However, waste management creates various problems from collection until disposal. As one of the best tourism islands in Malaysia, Langkawi receives a high entrance of tourists locally and internationally. As stated by the author, the tourists generated double

Table 1.2 Total weight of distributed newspaper in Three- to Five-Star Hotels in 2002 [19]

	Must-be available newspaper		Extra newspaper										Total
	SCMP	TS	USA	NYT	WSJ	IHT	FT	ST	MP	TKP	CD	JN	
Average weighted newspaper[a] (g)	402	145	85	333	115	160	125	584	602	262	75	155	
Standard deviation	8.91	29.40	26.18	28.13	11.14	38.43	18.93	28.02	32.62	38.27	34.12	3.16	
95% confidence interval	384.54–419.46	87.38–202.62	33.69–136.31	277.87–388.13	93.17–136.83	84.68–236.32	87.90–162.10	529.08–638.91	538.06–665.94	186.99–337.01	8.12–141.88	148.81–161.19	
Total no. of newspaper[b] (copies)													
Five-star hotels	1,963,842	726,354	470,784	67,255	551,490	413,618	137,872	349,726	209,835	69,945	69,945	349,726	5,380,392
Four-star hotels	3,437,663	1,271,465	1,177,282	–	946,534	466,204	–	708,724	939,471	–	–	470,913	9,418,256
Three-star hotels	948,713	506,980	63,248	63,248	63,248	–	–	727,347	347,861	221,366	63,248	158,119	3,162,378
Total weight of newspaper[c] (kg)													
Five-star hotels	789,464	106,321	40,017	22,396	22,396	66,179	17,234	204,240	126,321	18,326	5246	54,208	15,152,372

(continued)

Table 1.2 (continued)

	Must-be available newspaper		Extra newspaper										
	SCMP	TS	USA	NYT	WSJ	IHT	FT	ST	MP	TKP	CD	JN	Total
Four-star hotels	1,381,941	184,362	100,069	–	–	74,593	–	413,896	565,562	–	–	72,992	2,902,265
Three-star hotels	381,383	73,367	5376	21,062	21,062	–	–	424,771	209,412	57,998	4744	24,508	1,209,894
Overall weight (kg)	2,552,788	363,050	145,462	43,458	43,458	140,772	17,234	1,042,906	901,295	76,324	9990	151,708	5,624,531

SCMP = South China Morning Post, TS = The Standard, USA = USA Today, NYT = The New York Times, WSJ = The Wall Street Journal, IHT = International Herald Tribune, FT = Financial Times, ST = Sing Tao, MP = Ming Pao, TKP = Ta Kung Pao, CD = China Daily, JN = Japanese Newspaper

[a] The average weight per newspaper is found by measuring a sample of 100 newspaper

[b] Figures are derived from Table 1.2

[c] Total weight of newspapers = total number of newspapers × average weight per newspaper

solid waste per capita compared to residents and large amounts of wastewater that some goes untreated. The limited land and rapid urbanization, especially in the tourism industry, must drag Langkawi into a serious problem. The Geopark areas are prone to pollution and illegal dumping, which may seem the Geopark characteristics could deteriorate. The available treatment was unable to cope with a vast amount of waste generated and went to the landfill. The location of some islands that are far from the mainland causes the waste to not be transported, requiring the waste to be either treated or disposed of on the island [24]. Limited waste treatment will be made available on the island, especially for small sizes islands. A poor financial assistant could prevent the island from installing the best and efficient treatment facilities. Some small island depends solely on the allocation by the government or the stakeholder funding to manage wastes. Waste collection on the island is different compared to the mainland. A well-developing island with proper funding could have a modern collection vehicle while other lands still use door-to-door collection before heading to the landfill. In some islands in Indonesia, the wastes are burned or piled up as a method of disposal by the local community and stakeholders.

Waste fractions in tourism island mainly contributed by tourism activities. Organic and inorganic waste needs to be properly addressed to accommodate limited treatment methods. The solid waste generated commonly consists of 60–85% of organic waste and 15–40% of inorganic waste. The waste is further segregated and treated.

1.2.4 Cruise, Ship, and Yacht

Hoping on and off the cruise is becoming trending worldwide and enables tourists to visit several cities and even countries along the cruise routes. Restaurants, bars, and even shopping malls are made available on the cruise to allow the tourists to experience a unique experience on the cruise. The tourist can spend days, weeks, or even months, depending on the trip. The common solid waste generated is from food waste, plastic, clothes, and sewage. Nowadays, the cruise ship came in a larger size to allow higher capacity, thus it enables the ship-owner to gain more profits while reducing the cost for the client. The current state of cruise can accommodate around 5000–10,000 passengers per trip. With the large amounts of passengers, it is very important to provide them with a pleasant stay as well as a proper waste management system that satisfies environmental protection criteria. Around 4000 tonnes of gray water, 800 tonnes of black water, and 80 tonnes of solid trash and slime are generated by the cruiser. Due to the high level of environmental concern caused by such a large volume of garbage, it must be properly handled and threatened before being stored or released into the sea. MARPOL convention covers most of the ships for a country that accepts it. Polar cruise companies have grown in popularity in the previous decade, thanks to the Helcom standard, which covers a unique set of criteria for the dumping of wastewaters into the Baltic Sea. The most recent regulations are slated to take effect on June 1, 2021, for all current International Maritime

Organization (IMO)-registered passenger ships requiring AWP systems that meet the HELCOM standard. Ships frequently go through highly protected areas such as Alaska, the Northern Sea, and the Mediterranean, where wastewater discharge is strictly controlled.

Waste generated on the cruise can be divided into two, wastewater and solid waste. Wastewater can be classified into two, black and gray waters. Gray waters originate from showers, sinks, kitchen equipment, and similar sources, whereas black (fecal) fluids originate from toilets and ships' hospitals. Solid waste can be divided into various categories, including plastics, food waste, general waste, operational waste, kitchen oil, and incinerator ashes. Two common and highest amounts of waste produced on the cruise are plastic waste and food waste. Plastic wastes are obtained from regular waste and ship's kitchen in the form of wrappings, bottles, synthetic ropes, plastic bags, containers, and others. Plastic needs to be classified as contaminated or not as various pathogens can be found alive in contaminated plastics. Plastic waste can be handled by incineration or using grinders and presses. The incineration process for PVC burning cannot be applied unless the ship's incinerator is being verified by IMO. Besides using an incinerator, various grinders and presses are used to reduce the plastic volume. Food waste on the cruise is largely contributed by the kitchens and restaurants. The IMO has classified food waste as all fresh or rotten substances and further divided into soft and solid substances (bones). Most of the food waste is burnt via the ship incinerator. However, food waste is also allowed to be discharged under a few conditions; distances greater than 12 nautical miles from the closest land with plastic waste are fully separated from the food waste. As the cruise only have limited storage and space, the layout of the storage needs to fit perfectly to avoid any bad odor, maintain the safety and health of the crew and passenger as well as provide comfort to all people onboard. An average of 23 kg of food waste per passenger weekly can be obtained. Other wastes that contributed to the accumulated waste include general and operational waste, kitchen oil, and incinerator ashes. General waste is typically obtained in ships accommodation areas such as paper cardboard, synthetic materials, foils, cans, wrapping, glass, and excluding the food waste, plastics, and kitchen oil. Seventy percent of waste in this category is burnt, while other is pressed for volume reduction before being disposed of at the port. Various harmful chemicals are used or produced for the ship's engine room and during maintenance of ships systems (oily rags, batteries, oil packages, wood, paints, asbestos, and outdated pyrotechnics). As these types of waste are categorized as hazardous, proper and special holding is required. The incineration process is not considered the end of all wastes. The ashes generated by the incineration process are harmful as it contains sludge and sediment ashes. The ashes are packed into special bags located in metal boxes for temporary storage before being transferred and disposed of at port.

Waste generation on the cruise is complex due to limited storage, constant generation, long trip, strict disposal, and treatment. Both solid waste and wastewater need to be addressed carefully according to the standard and guidelines. Wastewater, as mentioned above, contains high levels of organic and oily substances and therefore requires modern and advanced wastewater treatment. Vilotijević et al. [25] have

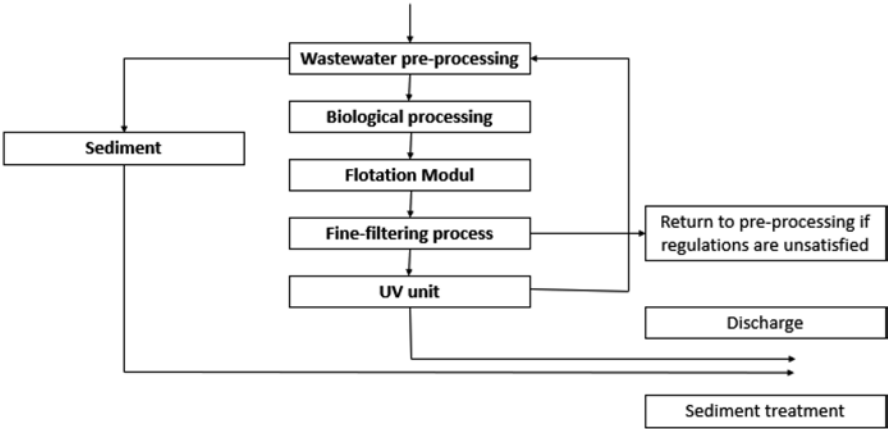

Fig. 1.6 Flow process of wastewater treatment [25]

suggested the flow process of wastewater on the cruise, as shown in Fig. 1.6. A detailed explanation of the flow process can be obtained in Table 1.3.

1.2.5 Historical City

Historical cities or areas seem to be one of the attracting factors for tourists, which may consist of an area of an old building or monument. Some historical cities are considered small with high dense of tourist which requires proper waste and hygiene management. Typical curbside collections have been demonstrated in several famous historical spots across European cities. However, such collection requires proper space, specific time for the collection to avoid congestion and peak tourist visiting time, worker accident and exposure to pathogens, and requires proper monitoring for odor and pest control to avoid bad images of the historical site.

According to Ciudin et al. [26], the historical center of Sibiu (Hermann Stadt), Romania, has taken another leap on solid waste management by integrating a vacuum waste collection system for their historical city center. Due to the drawbacks of kerbside collection, vacuum waste collection seems to become an ideal solution for a better and efficient system. Currently, the city center applied the conventional collection system that is environmentally unsustainable and partially not complied with the European Union directives and regulations. Garbage is dumped in containers placed along public rights-of-way; aside from their unsightly appearance, these containers are quickly filled, especially during seasonal events; at the same time, waste collection tracks wreak havoc on the city by crisscrossing old medieval roads, causing severe environmental damage. Another reason for using this method is because the historical area has narrow courtyards with limited room for garbage containers. Vacuum collection will drastically reduce the use of garbage trucks for

Table 1.3 The treatment process of wastewater and brief description

Treatment process	Description
Pre-processing	• Purifies and segregates larger particle and solid grease mechanically.
	• Pre-processing helps to prevent equipment damage down in the process. This will help to prevent clogging due to pieces of plastic or paper, cigarette butts, and others.
	• Common unit using rotating filter nets.
	• Collected solids are removed via automatic scrapper and transferred to sediment tank for further treatment.
Biological process	• Biological treatment is required for decomposition by microorganisms and oxidation.
	• Air is constantly pumped by the compressor to prevent organic substance settlement and to ensure oxidation.
	• Organic matter normally decomposes during this stage.
Flocculation process	• Smaller organic particles coagulate into bigger flocs by coagulant agents such as iron chloride and aluminum sulfate.
	• pH adjustment is required to obtain a value between 6 and 9.
	• Gray waters, especially from the ship's kitchen, are problematic and lose their pH value due to boiling.
Flotation process	• A pressure chamber is used to blow air at 4–6 bars to achieve waster dispersion.
	• Air bubbles that formed around the flocs force them up and transferred them to sediment tanks.
Fine filtering process	• The filtering process can remove particles of 40–60 μm using an oval filter.
	• Filter constantly washed with clean water to ensure flawless filtering.
	• Chlorine is added as a disinfectant, but a typical integrated ultraviolet module does not require any addition of chemicals.
Ultraviolet (UV) module	• The remaining bacteria, organisms, and viruses are removed via disinfection using UV.
	• Modern systems have 99.9% efficiency and are widely accepted as no chemical addition is required, such as chlorine.
TSS module	• TSS index of treated water must be lower than 35 mg/L before being discharged out.
	• If the treated water does not achieve the permissible index, the water will return to the fine filtering process.

collection as well as the traffic congestion, noise, and pollution. Vacuum collection systems consist of several collection points that are interconnected by a piping system to a centralized collection station. As the pipe network serves as a self-cleaning mechanism, the risk of fire is decreased. As a result, vacuum waste collection is more hygienic, and discarded waste is no longer affected by weather conditions such as rain, snow, or wind. This method will make street cleaning much easier.

1.2.6 Heritage Tourism

The World Heritage Convention, established in 1972 by the United Nations Educational, Scientific, and Cultural Organization (UNESCO), strives to designate and safeguard sites of Outstanding Universal Value for future generations. Glacier is considered as a Heritage site, and there are 19,000 glaciers present in 446 out of 247 natural World Heritage sites according to the UNESCO World Heritage list. Under a high emission scenario, the authors estimate glacier extinction by 2100 in 21 of the 46 natural World Heritage sites where glaciers are currently located. By 2100, eight of the 46 World Heritage sites will be ice-free, even in a low-emission scenario. According to the study, depending on the emission scenario, 33–60% of the entire ice volume extant in 2017 would be destroyed by 2100. According to Wang et al. [27], waste disposal is considered as one of the sources of heat released by tourism-related energy consumption. Data on the waste disposal and energy consumption from tourism waste disposal are crucial for conversion coefficients of energy consumption types. Research by Wang et al. [28] provides an insight into the effect of waste generation in the tourism zones of Yulong and Hailuogou. The research shows that a combination of waste disposal, shopping, entertainment, sightseeing, and human body metabolism contribute to 10% of tourism heat footprint (THF). The quantity of heat which is also known as anthropogenic heat release (AHR) emitted by energy consumption connected with aiding visitors during tourism activities (including food, lodging, transportation, sightseeing, shopping, entertainment, and waste disposal) is greater, accounting for more than 95% of total THF. The glaciers are particularly sensitive to temperature fluctuations; even a little shift in temperature may induce significant changes in a glacier [29]. Antarctica is another example of a tourism destination that is impacted by tourism activities [30]. Tourism development encompasses a wide range of operations related to the construction and upkeep of tourism-related facilities such as hotels, resorts, restaurants, and beautiful areas. Construction, tourism, and maintenance activities generate waste materials and energy, which have an impact on the environment.

Quick increase of waste generation and improper waste management in heritage cities cause an overloaded amount of waste in the waste treatment facilities [31]. The common types of waste found in the commercial waste of heritage cities involve biodegradable waste and recyclable waste.

1.2.7 Highland Tourism

For many vacationers as well as tourism providers, highland attraction is not a new phenomenon. Highland tourism has attracted many tourists for different activities. Highland tourism can be divided into several activities such as ecotourism, leisure activities, religious activities, and extreme adventure. The generation of solid waste in this area is arising especially during peak periods such as public holidays, religious celebrations, or any specific event.

Extreme adventure activities such as trekking and expedition are not excluded for having a serious problem in solid waste management. Trekking may be characterized as lengthy, strenuous treks, especially on foot, mainly for the sake of health, leisure, or pilgrimage. Expeditions are planned excursions with specified goals, such as reaching the summit of mountain peaks like Mount (Mt) Everest, doing research, or making discoveries in physio-climatically hard areas. One of the most common extreme destinations for extreme adventure is at the Himalayas Mountain. The number of visitors, tourists, or mountaineers is rising significantly under the name of mountain ecotourism or adventure tourism. As a result, the amount of human-caused pollution, such as solid waste, that is accumulated in these ecologically sensitive and topographically unstable mountain areas is increasing. If no official waste management entities are established and the absence of infrastructure services, self-generated "left behind" trash is the principal factor in increasing the trash burden in hiking and nearby places. There is also a need for a huge moral responsibility among the visitors and local communities to keep the area clean. Kuniyal [32] checks throughout studies the impact of highland tourism on solid waste management in Himalayan trails. The author classifies the waste into three different categories, readily biodegradable waste (RBW), biodegradable waste (BW), and non-biodegradable waste (NBW). The RBW is normally generated from human consumption and includes mostly vegetable rinds, leftover food, organic or unidentifiable materials, while BW consists of waste that can decompose naturally within a couple of months in normal temperature conditions, and NBW involves waste that cannot decompose and remain in the environment. Generally, the common leftover that can be found in Himalayan trails consists of non-biodegradable waste that belongs to the previous expedition. This waste being left open or covered with ditches in the camping areas. The risk for trekking activities is considered lower than an expedition. Thus, the trekking trails receive a higher number of visitors and are much more affected by waste problems. As for expedition, the generation of waste is still considered high due to the length of stay for expedition members as well the ecological sensitivities and lower local resource availability. Solid waste management in such regions requires special attention due to ecological sensitivity and topographic fragilities. In the subalpine and alpine environments, even a small amount of solid waste in one location might hinder the establishment of tiny plants, herbs, and grasses. Injuries and illness can result, for example, through water contamination, increased local temperature, and quicker melting of the glaciers. The per capita per day waste generation varied from 200 to 288 g in expedition and trekking areas, respectively. The setup of the waste characterization takes place in two different places, the Valley of Flower (trekking trail) and Pindari Valley (expedition trail). The composition of waste at these two places is shown in Table 1.4 [33, 34]. In general, waste in these compromises of RBW consists of waste compromised 12.2% (trekking activities) and 17.7% (expedition), BW contains 3.3% (trekking) and 15.9% (expedition), and NBW have 84.5% (trekking) and 66.4% (expedition).

Table 1.4 The composition of waste based on activities from two different sites [33, 34]

Type of waste	Valley of flower (*n* = 3)[a]	Pindari valley (*n* = 40)[b]
1. RBW	12.2	17.7
Food	2.4	3.8
Vegetables	7.9	7.4
Fruits	–	0.5
Beverages	–	2.0
Plant Residue	–	–
Fine organic matter	1.9	4.0
2. BW	3.3	15.9
Fruit seeds/shell	0.1	2.9
Paper	2.3	10.9
Clothes/rags	0.2	1.9
Wooden matter	0.7	–
Miscellaneous	–	0.1
3. NBW	84.5	66.4
Directly reusable	61.3	39.6
Polythene	2.6	5.1
Tins	–	9.5
Glass (bottle)	58.7	25.0
Candle	–	–
Nylon cloth	–	0.1
Decorative reuse	7.8	10.1
Battery	0.2	1.4
Bones/eggshells	–	1.8
Crockery	–	0.1
Paints	–	5.5
Hairs	–	–
Frooti wrappers	1.9	0.6
Processed leather	–	0.5
Mattress	–	0.2
Stone and bricks	–	–
Ash and fine earth	5.7	–
Recyclable	15.4	16.0
Plastic	4.7	8.0
Rubber	1.7	2.4
Metal	9.0	0.3
Glass (broken)	–	5.2
Needs safe disposal	–	0.7
Medical waste	–	0.7
Grand total	100.0 (72.2)[c]	100.0 (190.9)[c]

[a] "*n*" indicates the total number of the sample (1 ft^3) segregated
[b] Excludes human and packhorse excreta
[c] Values in kilograms indicate the total segregated wastes at a study site

The practices of waste minimization in the highland area are still low. Tourists, residents, and shopkeepers do not realize the potential of recyclable items. Not only that, but the residents do also not even care about the whereabouts of waste in their area due to a real lack of environmental awareness. Another problem faces are the mode of transportation of waste to bring the waste to a nearby town. There is no exact route that could allow the vehicle to reach the specific area; thus, all the waste needs to transport only by walking. Besides being time-consuming and energy-consuming, only a small amount of the collected items can be brought down. The shopkeeper in the trekking area only selects items that have a high margin of profit to be sold at the recycling center. The local government, host communities, and the tourist need to address the abundant waste by practicing good waste management, develop solid waste management options, including improving transportation, and create awareness among the communities. Kuniyal [32] suggests that authorities can establish a high-altitude solid waste collection centre (HASWCC) by using funding from recyclable waste and donations from any pro-environment organizations. The government could charge an environmental entry tax from ecotourists for environmental preservation and conservation. Furthermore, the government also can issue an order to request tourists pay a nominal entry tax and deposit all waste that they generated once the trip finish.

Religious-touristic activities take place in the highland area and generate a lot of solid waste, especially during the peak season. One of the popular destinations for these tourism activities can be found in a small hill town in Pahalgam, India which is also known as “Mini Switzerland” [35]. Pahalgam’s primary economic activity is tourism and attracts tourists from all over the world for both recreational and religious reasons (Yatra). Pahalgam receives more than 70% of the entire tourist traffic to the Kashmir valley. The tourists flow occurs in several months, which is the peak tourist season as well as the Hindu Religious Yatra period. Amarnath Yatra is a yearly religious occasion that brings pilgrims from all over India visiting the place to carry out religious occasions. The religious festival has been held for 7–10 days for centuries, but it has been expanded to 2 months in the recent decade. The management of solid waste in Pahalgam is having problems from collection until disposal.

The related problems do not happen in Pahalgam, but almost all hill towns in India facing common problems such as lack of budget, extreme climatic conditions, lack of modern infrastructure, lack of public awareness on waste, and difficult terrain. The solid waste generation in Pahalgam is estimated at around 18.72 tonnes/day, covering all activities in this town. The waste generator in this town and its amount can be seen in Table 1.5.

The solid waste generation by all the sectors depends on the social status and the living standard. Accommodation contributes the highest followed by households and other economic activities. The Amarnath Yatries occasion gathers all people around India and could be one of the greatest contributors of solid waste during the season and increase the burden on the solid waste management system. According to data from an EIA study by the University of Kashmir (Srinagar) in 2011, each Yatri is estimated to generate in average 2 kg of solid waste and assumed that Yatra

Table 1.5 Composition of waste based on the waste generators

Waste source	Composition (%)
Hotel and restaurant	74
Households	18
Market	5
Street sweeping	2
Commercial	0.5
Others	0.5

occasion solely generated 2.84 tonnes of solid waste per day. Shop in this area generate 7.8 kg of waste on average and could increase up to 2.41 tonnes in total daily for all shops in tourist season. Another waste generator involves street sweeping, which contributes about 1.1 tonnes of street waste during tourist season. Generally, the composition of waste consists largely of compostable and recyclable waste. The only segregator of solid waste in Pahalgam is rag picker beside the household itself. However, the rag pickers only work during the peak tourist season, which allows them to maximize the selling of recyclable items.

The collection of solid waste in the hill town of Pahalgam is still considered not efficient enough and poor. The only available services are door-to-door collection, collection from primary and secondary bins, and some of the waste may be openly dumped. The accommodation, such as hotels located near the main road, is likely to provide a door-to-door collection while those located far would dispose of their waste in the community bins. The municipalities have provided households with community bins to allow the better collection of solid waste. However, the access to the community bin is poor, and the location is considered far. The commercial and marketplaces are also considered to have poor access to these bins. The transportation and disposal of solid waste have been poor, with limited sources and treatment options. During the peak tourist season, the collection services are beyond municipal limits and carried out manually using a municipal sweeper to the dumping ground without proper transporter. The wastes are openly dumped on an open forest space near the town's major roadway and a freshwater stream coming from the nearby lake. Water-borne diseases attack the valley every time during peak tourist season and Yatra season due to the water pollution because of open dumping near the riverbank. The water stream is used as a drinking water source without any treatment due to the consideration that the water is pure and clean. The open dumping areas have demolished important vegetation cover and pine trees. The dumpsite area is also inviting local livestock, dogs, and other animals to this area.

In northern Thailand, Chiang Rai is the second biggest city consisting of both highland and lowland zones. The cool temperature and fresh environment are the main attractions for tourists to visit here. Given the typical morphology (elevated regions) of the provincial highlands, restricted roads, and restricted disposal locations, waste separation, transport, and disposal are even more problematic. During the peak season of tourists, extensive waste generated and increased the burden of the solid waste management system. According to Laor et al. [36], the understanding of municipal solid waste (MSW) is considered high, but the implementation and attitude are still in between low and moderate. The knowledge, attitudes, and practices (KAP) of solid waste management are crucial for all levels of age. These factors are vital to guarantee the long-term effectiveness of MSW management strategies by understanding public concerns, knowledge, and behavior. The waste collected in Mae Salong Nok highland, Chiang Rai Province, is collected and sorted [37]. The waste is then segregated into four different types of waste, which are general waste, organic waste, recyclable waste, and hazardous waste, as suggested by the guidelines of Thailand's Pollution Control Department. KAP study is also being carried out by using questionnaires and interviews. The waste generation rate in this particular tourism area is estimated to generate 1.74 kg per night for a single tourist [38]. However, Suma et al. [37] stated that the actual amount of waste should be beyond the estimated value because some of the waste is left uncollected due to high-slope areas, narrow roads, which lead to inaccessibility for solid waste collection. Table 1.6 shows the type of waste generated in this area and the amount generated.

According to the survey carried out, 62.3% of the 236 survey respondents were female, 35.6% were between the ages of 20–40, and 22.5% were between the ages of 41–60. 23.3% were under the age of 20. 35.2% of respondents were merchants, followed by students and tourists (18.2%) and freelancers (11.4%). Respondent responses were used to determine the respondents' degree of KAP about MSW management. The ratings suggested that respondents had a good degree of knowledge (80%) and attitude (76%) about MSW management. However, at 37%, the amount of practice for MSW management was startlingly low. At the national and local levels, Thailand currently lacks effective environmental education and awareness efforts [39]. The language barrier is one of the main reasons for unsuccessful MSW management campaigns that are already being carried out as Thailand consists of a variety of hill tribe ethnic groups. Based on the result of the study, the finding shows a low implementation of MSW management among the tourists, merchants, and business owners compared to the resident. Separating food and organic waste for animal feed and/or composting is advised to minimize overall waste volume, cut transportation costs, and decrease environmental concerns.

Table 1.6 The waste composition and their amounts

Waste categories	Materials included	Amount (%)
General waste	Plastic bags, non-recyclable plastics, foam boxes, non-recyclable paper	29.19
Organic waste	Food waste, garden waste, leaves, grass, branches	42.79
Recyclable waste	Glass, paper, recyclable plastics, milk cartons, aluminum cans, metals, tires	26.53
Hazardous waste	Pesticide containers, batteries, pieces of electronic, fluorescent tubes	1.49

1.2.8 Entertainment Park/City

The existence of an entertainment park is necessary to develop and promote healthy lifestyles as well as reducing the working pressure. The actions of visiting the entertainment area such as the park could boost the social links, especially for those that came in a large group such as family or colleagues. However, activities carried out in this area could lead to the generation of solid waste, which requires proper management. According to Mahdi et al. [40], an average of 0.759 kg/person/day and 225.00 visitor/day in army channel entertainment park in Baghdad results in 35.550 kg/visiting day that is approximately 35.550 tonnes/visiting day. The composition of solid waste generated in the park is described in Table 1.7.

The zoo is considered as one of the important entertainment players that provide entertainment, education as well as preservation and conservation of endangered species. The zoo's animals and visitors create a significant quantity of solid waste. Inside the zoo, all animals and visitors generate a huge quantity of the trash, which includes both organic and inorganic waste. Zoos with access to millions of people can teach and communicate with many people about living a sustainable lifestyle. The zoo may make a significant contribution to a more sustainable future by incorporating sustainability into its policies, plans, and management. A variety of parameters like expenditures, environmental effect, profitability, complexity, and sponsorship are considered. Pathak et al. [41] provides an insight into the management of solid waste in Lucknow Zoo, India. The Lucknow Zoo now has 468 mammals, 378 reptiles, and a variety of wild animal species. The zoo also successfully breeds various kinds of animals and is home to various plants. In addition to these features, the Lucknow Zoo draws 900,000–10,000,000 tourists owing to which it has high amounts of solid waste creation. Waste generated can be divided into three groups (animal waste, biomass waste, and anthropogenic waste). Common solid waste generated includes polythene bags, wrappers, papers, plastic bottles, and waste from the cafeteria beside the massive amount of organic waste produced by the animal in the zoo. As per the survey carried out by the author, the amount of waste generated by animals and plants is listed in Tables 1.8 and 1.9. Animal and biomass waste with high organic content is commonly treated using biological or thermochemical conversion. Variation of animal waste is contributed by factors such as digestive physiology of various species, composition, and form of the diet

Table 1.7 Solid waste categories and total generated wastes of each category per visiting day

Waste category	Total generated wastes (tonne)	Rate of the waste category (%)	Total wastes/visiting day (tonne)
Food	35.550	62.2	22.112
Glass		6.1	2.168
Paper		13.7	4.87
Cans		10.4	3.697
Plastic		7.6	2.703
Total		100	35.550

Table 1.8 Quantitative measurement of the fresh animal waste in the zoo premises

Animals	No. of animals	Waste generated per day
Himalayan black bear	3	1 lb × 3 (1 kg = 2.2 lb)
Sloth bear	3	1 lb × 3
Giraffe	2	5 lb × 2
Rhinoceros	1	1000 lb × 1
Swamp deer	57	3500 g
Barking deer	23	3500 g
Hog deer	30	3500 g
Sambar deer	15	3500 g
Spotted deer	198	3500 g
Rabbit	10	2800 g
Total	342	482 kg/day

Table 1.9 Quantitative measurement of the fresh animal waste in the zoo premises

Sources	Composition
Twigs	Approx. 2 kg/day
Dry leaves	Approx. 3.5–4.0 kg/day
Total	Approximate 6.5–7.0 kg/day

and stage of growth and productivity of the animal. Meanwhile, plant-derived waste depends on the composition and nature of biodegradability.

Several theme parks in the Philippines, especially in the Subic Bay Freeport Zone, counter the problem of solid waste management by implementing green practices that may reduce the burden on the current SWM system. Matriano et al. [42] reported that the companies manage the theme parks using the 3R (Reduction, Reuse, and Recycling) concept, which applies to all management, staff, and customers in all their facilities. Equipment and toiletries are replaced with high-efficient equipment and reusable material. The procurement of condiments, cleaning supplies, and other durable products are normally purchased in bulk and concentrated form. The managements also initiate collaborative efforts involving all owners, stakeholders, and employees to ensure that efficient action is taken to maintain a good image and practices.

1.2.9 Shopping Tourism

Shopping is one of the most popular and fun things that people do while on vacation, and in many cases, it serves as a significant draw and primary motivator for travel. People have been able to go further afield to shop due to the recent rise of more efficient transportation networks, more technology, and widespread usage of

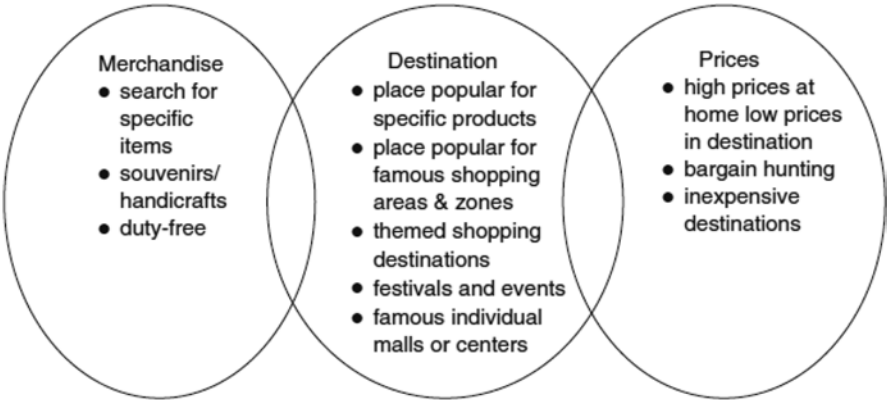

Fig. 1.7 Factors contributing shopping as a motivation for travel [4]

credit cards. The connections between shopping and tourism may be classified into two types [43]. The first is where the main goal of the tourist journey is to shop. The second is when shopping is done as a side activity during a journey that is primarily driven by anything other than shopping, such as sunbathing, ecotourism, and others. The function of shopping as a type of tourism is first considered in terms of the things purchased, the chosen place, and price advantages/value [4]. The item being sought, the place is chosen, and price benefits stand out as the driving forces behind shopping as a key cause for travel, yet as Fig. 1.7 indicates, these elements may overlap and operate together as motivations for travel. These elements do not have to be mutually exclusive. They feed off one other.

Shopping is a deciding element when it comes to deciding travel destinations. Shopping can even be a key motivator in influencing travelling purposes [4, 44]. Twenty eight percent of passengers decided their destination for shopping and fashion options. Research by Ric et al. [45] shows that their respondents travel abroad; up to half of the instances occur at least 3.5 times in a calendar year. Fewer than a third of respondents travel overseas more than twice a year. The remaining 20% travel overseas at least eight times every year. The study also notices that on their vacations, 29.5% of travellers intend to visit a clothes store, while 63.5% do not. Sustainability in tourism, especially shopping, has been significant for the decision-making of a tourist. Public knowledge on sustainable tourism is essential for reducing impacts on economic, environmental, and social sustainability.

1.3 Type of Tourism Waste

Tourism waste is the residue leftover from the tourism ecosystem's consumption of natural resources. The nature of the profession or consumption has a significant impact on the ecosystem and ecology. Tourism waste is quickly becoming a significant constraint to and influence on the long-term growth of tourism destinations. Tourism waste can be classified into four main groups (food, plastic/packaging, biodegradable, and inorganic waste). These groups contributed the major amount of waste and for almost all the waste sources.

1.3.1 Food

In general, food waste nominates the highest amount of waste generation in almost all tourism waste sources. The demand for food never stops and shall increase especially during the peak season of tourism activities. Special promotion for foods and the buffet concept is one of the reasons the generation of food beyond the consumption demands. Food demands are also needed for other living organisms, such as animals in zoos. The excess of food consumption either for tourists, staff, and animals contributed to food waste.

Food waste that is released in the ocean is biodegradable and normally will feed the fish. Even though food wastes are biodegradable, the degradation period is still different depending on their type. Fruit skin for example normally takes a longer period to degrade and possibly to travel back to the beach or nearby land, thus presenting a bad image along the shore. Not only that, but the presence of food waste may also invite rodents, animals, and birds, which will bring bad impressions as well as bad odor for tourists. Tourist normally considers all aspects of before vacation plans.

Food production contributes to climate change due to its significant resource use [46]. Uneaten food consumes resources for manufacture, transportation, storage, and preparation and—when disposed of—releases methane, which "warms the earth 86 times faster than CO_2" [47]. In general, foods are wasted and lost in various stages throughout the preparation until consumption. Data provided by HLPE [48] in Fig. 1.8 present the overall percent loss of food waste for different regions.

1.3.2 Plastic/Packaging

Plastic and packaging are materials that can last long in the environment. Plastic and packaging are used for packaging goods, food containers, toiletries, bags, bottles, and wrappers that can be found everywhere in the tourism sector. Pollution due to plastic waste can have a detrimental impact on lands and the ocean. Plastic waste can bring bad images to tourism sites and could influence the decision for tourists to visit. Plastic wastes take a longer time to degrade, and some may not even degrade and last forever in the landfill. Another impact of plastic littering, especially in the ocean, will settle in the seabed and disturb the marine ecosystem. Plastic pose both physical and chemical threat. The presence of plastic will cause entanglement, gastrointestinal blockage and pose destruction to the reef. Bioaccumulation of plastic

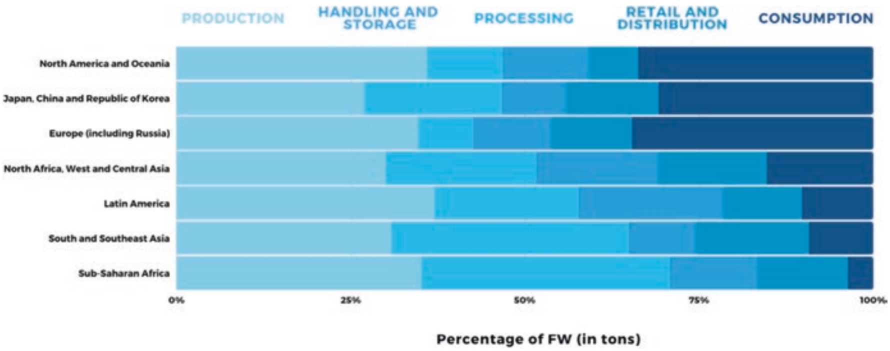

Fig. 1.8 The distribution of food waste lost in various stages in the different regions [48]

waste and/or toxic chemical sorbed in the plastic when consumed by the sea creature.

1.3.3 Biodegradable

Biodegradable waste can be defined as a material that can degrade and decompose naturally. The typical natural agents for the degradation of waste include sunlight, microorganisms, water, and ozone. Biodegradable waste has the potential along with food waste which can be retrieved into value-added products. Biodegradable waste is considered as nontoxic as its only compromise of natural materials and considered eco-friendly. Common biodegradable waste that can be found in the tourism industry includes fruits, vegetables, flowers, plants, animals, water, paper, fecal, and many more. The common contributor of biodegradable waste can be assumed as kitchen waste by the tourism provider and waste from zoo management.

1.3.4 Inorganic Waste

Inorganic waste is made up of synthetic and has little effect or no effect from the microorganism decomposition process. The inorganic waste such as glass and tin cans cannot be degraded and can float around or be sinkable. Other inorganic waste includes paper and cardboard. Inorganic waste can be either recycled or disposed of depending on the conditions of the waste. Waste minimization and recycling can effectively reduce the amount of inorganic waste, thus reducing the burden of the landfill. Some organic waste poses a slow degradation process, and some may even present after 500 years. Plastic is still considered as one of the inorganic wastes that create a nuisance for the environment.

1.4 Management of Waste

The collection, transportation, processing, recycling, or disposal of waste products, as well as their monitoring, are all part of waste management [49]. Collection, transportation, pre-treatment, processing, and ultimate residual reduction are all part of a typical waste management system. However, throughout the process, waste can be reduced via minimization and recycling, which may reduce the burden for final disposal.

1.4.1 Generation

The generation of waste by the tourism industry is undeniably massive, and proper reduction and recycling are needed. In the tourism industry, the generation of waste can point into the tourism industry player and the tourists themself. Tourism providers equipped the guest with several toiletries and materials that may be contributed as waste once finished. Non-eco-intelligent purchasing leads to massive waste generation. The consumption of food, whether fast food or cooked food, in daily life is another point source for waste generation. Excess of food and fast-food containers contributed to waste generation. The demand for food, which is one of the basic needs, will be consumed repeatedly every day, and tonnes of waste will be generated unless the consumption of food has been reduced. The habit of shopping also leads to the generation of abundant plastic and packaging when the reusable bag is not enforced. The purchase of goods often comes with proper packaging and sometimes can be considered excessive, which may lead to waste. The need for entertainment led to the opening of zoos and theme parks. Both organizations contributed a significant amount of waste and wastewater. The zoos, which are the habitats of endangered species of animals and plants, produce a large amount of waste via the food waste of animals, green waste, and fecal of the animal. Theme parks require a large amount of water for water games, and water replacement is needed after a certain time of usage, thus been released or treated. Wastewater cannot be excluded from the implication of the tourism industry as the generation directly correlates with the number of tourists. Both waste and wastewater also can be found on ships and cruisers.

1.4.2 Collection

All ships, cruises, and even yachts are equipped with a storage setup for temporary hold of solid waste and wastewater before being transferred to the nearby port once full or finished the trip. In some modern cruises or ships, high-end equipment such as incinerators and advanced wastewater treatment is already used to treat both solid waste and wastewater onboard. This equipment helps to reduce the amount for storage system and even treat the waste so that it can be released into the sea. Normally, this type of vessel carries out a solo trip for tourism purposes or other specific purposes. On the certain occasion that involves a high number of ships and yachts such as the mass event of ships and yachts, organized and proper planning is required to ensure a smooth collection process. A poor organization may disrupt the event, poses a danger to the participant, and even environmental pollution. Mismanagement for collection time could delay the event and gives a bad aesthetic impression which could lead to the reduction of revenues for the event and possible nearby business entities. Lapko et al. [50] summarized the waste management and collection from yachts and tall ships during Tall Ship Races (TSR) in four stages:

Stage 1: Informing about willingness to dispose of waste
Stage 2: Waste collection
Stage 3: Confirmation of collection
Stage 4: Confirmation of waste acceptance

Time management is important in waste collection due to the large involvement number of vessels and limited time to collect from all vessels. Tankers and slurry tankers are used to receive liquid oil waste and sewage from the vessels. In some cases, a long hose needed to be used to collect liquid waste collection from the vessels, which could drag sometimes. The vessel officer will be needed to confirm the waste collection by the collection company for documentation purposes. For solid waste cases, the waste will be transferred into tank trucks or any collection vehicle to be sent to landfills or any treatment facilities. Yacht owners or tourists need to follow the existing standard procedure. All waste should be transferred to the marina at a specific collection system. Solid wastes are transferred into the container at the marina, while sewage from the portable toilet goes into sanitary installation. Sanitary sewage from the solid reservoir and bilge water is pumped to the collection system in the marina.

The mainland and island collection system may be different for waste handling. In developed countries, the collection of waste is not a major problem with a proper collection system. Some country powered by a transfer station to ensure optimum waste collection and transport to a disposal site. Advanced collection system such as vacuum collection system has also been implemented to provide a clean and hygiene collection system in some cities. However, the financial constraint and geographical difficulty lead to an inefficient collection system. Both factors badly affected the waste management system, especially in developing countries. Generally, the collection of waste should be carried out using proper vehicles with proper mitigation measures. Unfortunately, some country unable to provide sufficient waste collection, and some of the countries rely on manual segregation and collection as well as the private sector to overcome the massive burden of waste management.

1.4.3 Disposal

Incineration of waste seems to be an ideal solution for waste, especially in metropolitan cities having a problem with land scarcity for landfill opening. Large generation at the same time requires a fast and modern treatment system. The increase in tourism will increase the generation of waste. Incineration rises as one of the options for reducing the amount of residue that needs to be landfilled. The like of metropolitan cities such as Tokyo and Kyoto in Japan receives a high number of visitors as well as generating a vast amount of waste via service industries (hotel, lodging, restaurant, and other complementing industries) [51]. In Kyoto, 15% of waste generated from livestock excreta and corpses is incinerated to reduce the burden of the landfill. Despite the benefits, experience has demonstrated that incineration is also extremely damaging to the environment. Numerous anti-incinerator campaigns have been undertaken over the world due to the environmental threat they pose [52].

In some of the developing country, waste that is not properly managed or not collected are burned or dumped. The consequence of this event will create a bad odor and reduces the aesthetic value, especially for tourism destinations. Tourism spots that are isolated often dispose of waste illegally and without proper disposal. Although landfilling is the least preferred for waste management, the current state of waste management worldwide, many countries still apply landfilling as their major practices. The inability of countries especially developing countries, to be equipped with a high and modern treatment system is the reason for the selection of landfilling as the main disposal method. The term "landfill" refers to another frequently used method of waste management in which rubbish is collected from one region and dumped in a less populous area. In essence, it is a well-planned depression in the ground or a structure constructed on top of the ground into which garbage is placed. This provides a convenient disposal location for waste created by a municipality, city, or industry. Landfilling harms groundwater, soil, and air.

1.4.4 Recycling

Generally, the responsibility of waste recycling should be shared between the government and private sectors. Recycling, or at the very least energetic recovery, has several advantages over other waste disposal methods. It lowers production costs, decreases landfill demand, conserves energy and natural resources, and creates job opportunities [53]. Developed and developing countries have different systems and financial means to achieve optimum waste recycling rates. The recycling rate for both types of nations will also show different data because of awareness and the recycling system. According to Troschinetz et al. [54], the planning for a systematic recycling system, especially in a developing country, should focus on three dimensions of sustainability involving waste collection and separation, municipal solid waste management plan, and local recycled-material market.

Tourism city is one the main attraction for tourists and local people. The city is the focal point for employment, administration, and tourism. The dense population in the city plus the incoming tourist create heavy traffic for solid waste management. A city in a developing country such as Hoi An City in Vietnam is one the popular attraction for tourists. As stated by [55, 56], the recycling rate in this city is low and influenced by a weak driving force, and there are numerous obstacles to recycling in the commercial sector even though the recyclable item is quite high, 78.7% for domestic waste and 84.3% for the hospitality industry. The recycling system in this city is divided into two, informal sectors and formal firms. Informal sectors can be considered as itinerant buyers, street pickers, collection teams, scavengers, and junk shops at treatment sites collect recycling material directly from residents in the area, while the formal sector involves the public work company. Typically, the itinerant buyers and street waste pickers are a poor and neglected social group that trade recycling material as their source of income [57]. Loan et al. [56] stated that residence in the city did not segregate waste unless they understood the benefit and positive impacts of this action. In big cities with a high understanding of waste management, the recycling rate is high for certain waste categories compared to generation. Thus, reducing the negative impact repercussion of tourism [51].

Recycling schemes, especially for highland and remote areas, are concerning the issue of transportation and costs. Due to improper collection and transportation of solid waste, waste is normally dumped openly and causing bad odor and reducing the aesthetic values. For tourist that enjoys extreme highland tourism such as trekking and expedition, the self-generated waste can be considered as a burden, and the responsibility falls under them. At a certain height or area, no proper management of solid waste, as well as maintenance, is being carried out. Under the circumstances, the wastes (recycle waste and non-recycled waste) management will be dependent on the voluntary behavior of the visitor [58]. Organic waste recycling can still be carried out even at high altitudes. The community or tourist can utilize a micro-level bio-composting practice. This method can be carried out by digging small-size pits in down-slope snowlines zones and away from water sources. Due to the extreme continually growing high biotic pressures and human meddling in these places, such micro-level bio-composting pits would have to be dug out below the snowline, causing the least amount of harm or loss to the Himalayan glaciers, which are currently receding. This aerobic high-altitude bio-composting may be applied to depleted meadows and pastures, as well as existing dwarf types of plants like Rhododendron campanulatum, as compost nutrients. Due to transhumance practices, tourism, hiking, and/or expedition activities in the central and northwestern Himalayas, these grasses and dwarf variants of tree species, which thrive in locations of bad soil and climatic conditions with a restricted growth season, are under strong biotic pressure. Vegetation growth can be enhanced, and these regions may be ecologically managed, resulting in better circumstances for animals and humans by delivering these nutrients through micro-level bio-composting processes.

Commonly, the key player for recycling initiatives on the island is driven by the private sector. The impacts of the private company such as Perme in Greece has helped the country to meet the statutory of EU recycling and landfill diversion targets. Perme is one of the companies that deal with recycled glass and cardboard from the source, thus reducing the amount of glass and cardboard dumped in the landfill. Perme provided the hotel with bottle banks to ensure the segregation at source and an efficient recycling scheme. The collaboration between the private sector and tourism players provides a smooth flow for waste recycling and provides a win-win situation for both parties.

A similar approach can be carried out for recycling and reusing of waste generated on cruise ship. The initial segregation at the source, which involves the segregation of waste on the cruise ship, will enable the waste to be subgroups for reuse and recycle purposes. Once reached the port, the unwanted waste can readily be transported for disposal while the recycled and reused one can be sold to any relevant organizations. One of the examples of waste that can be recycled includes oily wastes, which can be processed into a new oil product. According to Svaetichin et al. [59], the practices of recycling by the cruise ship-generated waste have been well established, especially in several ports along the Baltic Sea, although just been introduced for not even a decade. The capability of each port to recycle above 50% of cruise-ship-generated waste provides a good insight that waste recycling can be carried out from this vessel.

1.4.5 Minimization

Cummings [60] defines waste minimization as "tactics that effectively will ease waste disposal needs by actually quelling the quantity and toxic nature of goods used, waste generated, and waste requiring disposal." Waste minimization is a "proactive and suggested solution for environmentally conscious operations," according to the study. Waste management requires a shift in practices and the elimination of issues at the roots rather than coping with them later. The image and cleanliness of tourism destination need to be properly maintained to ensure the attractiveness and aesthetic value is preserved [61]. As reported by Todd et al. [62], the waste minimization initiative has managed to reduce hotels disposal costs by 60%. Waste minimization aligns with the tourism industry's financial benefits as well as the need for environmental protection [63]. Cummings [64] has established a five-tiered solid waste management (SWM) model that includes:

1. Demonstrate a commitment to waste reduction
2. Make environmentally purchases
3. Make effective use of resources to produce revenue
4. Purchase reusables and reuse them
5. Acquire reusables and reuse them as recyclables, and properly dispose of them.

Eco-intelligence is purchasing such as acquiring products with a longer lifespan, using eco-friendly cleaning products, and making bulk purchasing are common steps taken to minimize waste generation and save the cost [65, 66]. However, the awareness and implementation of purchasing recyclable goods or products is still low and does not meet the expectation [67].

Hotels, restaurants, and hospitality can minimize the waste generation by procuring reusable, donating, or reselling used furniture or equipment and donating good quality food excess [68, 69]. Another way is to ensure that a long-lasting of equipment is by servicing it regularly. Implementation of waste minimization practices has been inconsistent across time and geography, with recent studies focusing primarily on one field (i.e., lodging). Food is another waste source that is generated by the various components in the tourism industry. Besides retrieving the organic compound into value-added products via composting, other alternatives can be carried such as developing a purchasing guideline for durable and reusable products. Excess or unused food can be donated to nearby food banks and humanitarian foundations, while food waste can be adopted as animal feedstock [37].

1.5 Impact of Tourism Waste

The impact of tourism waste can be divided into three components: environment, financial, and economy. Each component is severely affected and requires proper attention.

1.5.1 Environment

The environment can be severely affected by the massive generation of tourism waste. Improper waste management can have serious and irreversible environmental consequences, including increased greenhouse gas emissions, land degradation, resource depletion, surface and groundwater contamination, and biodiversity loss, as well as the erosion of tourist destinations' aesthetic value [23]. In general, the waste of the tourism industry can be found in two forms, solid waste and wastewater. Waste and litter that have not been properly maintained are unsightly, giving visitors a negative impression of the country. The quality of the groundwater supply can be directly impacted by improper solid waste management. When solid waste, which is mostly organic, comes into contact with water, it starts to decompose and then takes the dissolvable waste components with it. The pollutants in this polluted groundwater (leachate) will disperse well beyond the local contamination region. The leachate also could reach water resources such as rivers, streams, ponds, and wetlands. Once the water resource is contaminated, the water is no longer safe for drinking purposes and domestic usage. The poor management of solid waste also will lead to the breed of mosquitoes and other vectors that can cause disease outbreaks. Hence, a close precaution must be taken on the vector's control and the safety of the community as well as the tourist.

The pollution of solid waste does not only happen on land, but a variety of waste being also dumped in the ocean, especially in the tourism area that is not properly managed. One of the most difficult-to-solve global waste and resource management problems has emerged: plastic waste in marine litter. Particularly in the case of nations that have a coastal area, plastic is the most common form of waste found on beaches and sea that will last for a long time due to poor solid waste management (SWM). Another marine waste is known for having slow degradation causing an accumulation in the coastal area. As a result of pollution or other marine debris, the image of the beach changes quickly, and travellers are quick to switch their plans to different activities [70]. Pollution of waste in the ocean can cause coral reefs and aquatic life to be threatened. Excessive growth of unwanted algae will lead to the loss of biodiversity, breeding, and nesting grounds and affect the attraction of tourists. One of the best attractions deep down in the sea is the magnificent and rich biodiversity of coral reefs. However, coral reef environments are highly vulnerable to climate change [71]. Three common factors are deemed as the main reason for coral reef destruction. Finite physiological tolerance ranges for environmental conditions, susceptible to pollutants stress and the change in climatic conditions of a coral environment with the presence of toxic pollutants [72–74]. The increase of nutrient levels such as nitrogen and phosphorus, as an example, leads to uncontrolled algal growth that will demolish the coral reef ecosystem [71]. The dead coral reefs will disturb the ocean ecosystem, reduce the values, and require conservation. The cruise ship industry contributes major impacts on the environment, especially the ocean ecosystem. Accidents that happen may contribute to oil spillage or leaking, thus contributing to pollution [59].

Environmental pressures from Antarctic tourism include polluting, non-polluting, and interregional effects. Site degradation, waste generation, wildlife disturbance, fauna and flora illnesses, ice layer deterioration, and freshwater use are all major negative impacts of tourism activity.

Waste produced in highland tourism is difficult to be handled and often left dumped, resulting from direct and indirect contributions to pollution in the environment. Wiangnon et al. [75] reported that bad weather would wash the accumulated dump waste, which results in soil and water pollution. The consequences of the waste runoff could lead to waste end up in the community, agricultural, or any commercial area in the lowland. Other issues that could arise due to open dumping are the burning of waste. The transition of monsoon could cause the fumes to fall into the basin instead of the rise and cause the burning haze that harms the environment and health.

1.5.2 Financial

Financial demand for waste management is necessary for various kinds of action in waste management. For tourism providers, the management of waste within their premises requires spending on the appointment of staff or any contractors, especially for large-scale entities. The costs for waste to be transported from any island back to the mainland require extra cost, and at a very small scale, some of the providers would consider illegal action instead of spending. Some other providers have taken extra steps by utilizing recycling and composting to reduce the costs. Millions of dollars in future landfill management and pollution mitigation expenses can be saved by reducing solid waste entering landfills by up to 20%. Sealey et al. [76] provide an example of cost consumption of solid waste management by the tourism provider in Fig. 1.9. Consideration of various factors, including the waste management and mitigation of dumps for the long term, especially to a locality that still lacks waste management legislation, is needed immediately. Environmental and public health consideration management should be prioritized to protect not only the tourist but also the management and the image of their organization. Tourism providers should also not be afraid of embracing new technologies to achieves immediate impacts at a higher success rate.

Progress can be made through innovative private sector collaborations that foster community support for plastics, metals, paper, and used oil recycling. While sanitary landfills are costly to build and operate, the whole cost of solid waste management remains invisible to residents and tourists. Delay in maintaining and expanding the local landfill raises the long-term expenses of pollution mitigation and remediation. Tourism expansion may need upgrading infrastructures such as waste management systems, landfills, and sewage systems. Composting and recycling on a wide scale are two of the most effective strategies to reduce solid waste expenditures. Government waste disposal legislation must establish long-term financial mechanisms to promote collaborations focused on solid waste reduction.

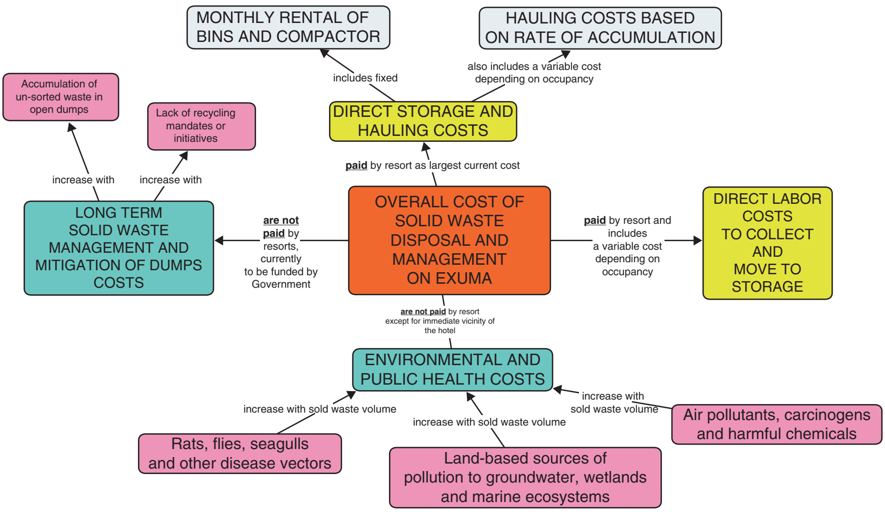

Fig. 1.9 The concept diagram of the cost of solid waste management

1.5.3 Economy

The economic growth of the nation can be influenced by the thriving tourism industry. The local authorities need to take a systematic approach to maintain and preserve the aesthetic value of tourism attractions. A tarnished reputation may have serious economic implications for the local tourism and leisure industries [70]. Ensuring a clean tourism area is a key service and supports social and economic activities in tourism cities [77]. The economic downfall had been faced by Tunisia in 2016. The country released an average of 8.5 ktonnes plastic waste every single year into the Mediterranean Sea. The action causes the Tunisian Economy to lose $20 million a year and affects the tourism, shipping, and fishing sectors due to serious plastic pollution [78]. Participation in a waste management program gave direct economic benefits to hotels (via trash minimization), indirect benefits such as an improved corporate image, and saved costs, according to one of the studies conducted in Bali (liability) [79].

Recycling waste could increase the economic value and reduce the cost of solid waste management. Composting such as example could provide an economic link with the agriculture and landscaping sector. The large scale of composting requires labor and management of the market. This will eventually provide job opportunities to local communities. Composting, sorting, and repurposing waste not only protects the environment but also adds a new dimension of economic activity, supports small-scale agriculture, and improves socioeconomic well-being. Zero waste means that no solid trash is dumped or disposed of and that all materials are composted, burned (for energy), repurposed, or separated for export to bigger markets. Zero waste can be the pinnacle of environmentally and economically sustainable tourism promotion. Governments can gain from integrated solid waste management in the long run by lowering landfill management costs and generating additional income through regulation and waste disposal fees. When economic criteria are fulfilled, aluminum, scrap metal, and electronic trash can be stored and exported to generated income from the waste.

1.6 Sustainable Green Tourism Industry

Tourism is now beginning to focus on long-term sustainability. Sustainable tourism is described as tourism that considers the current and future social and environmental consequences while still meeting the demands of visitors, industry, the environment, and host communities. The notion of sustainability refers to the environmental, economic, and socio-cultural components of tourist development, and it is necessary to strike a fair balance between these three dimensions to maintain long-term viability. Since the last century, environmental concerns have been voiced loudly by non-profit organizations and scientists. The impact of this movement has created awareness regarding the importance of purchasing environmentally certified products [80]. Even though the environmental-friendly requirement is not the only reason for purchasing goods, other credentials aspects such as quality and affordability should be prioritized by the producer. Due to the claims by various companies on their eco-friendly product, no proper justification on the high prices for the products and environmental improvement that can be achieved are the main reason why these products are not able to compete with the current product in the market. The definition of a green commodity is simpler to apply than to describe. In broad terms, a good or service is considered green whether it benefits both the manufacturer and the customer while causing no harm to the environment. The finance market, on the other hand, has some of the lowest ratings. Tourism has historically been regarded as a comparatively green sector, except for its consequences for transportation and land growth, and as a result, it has only recently become a source of concern. The terms ecotourism, green tourism, and soft tourism are all used to refer to environmentally sustainable tourism, but they all have distinct meanings and focuses. The mentioned terms are used for two main intentions [81]:

1. Promote the tourism destination for still being untouched, well preserved, and beautiful.
2. Claiming the tourism activities/area carried out does not harm the environment.

The terms used somehow being used by the industry to reasonably open up new areas for the more discerning (and expensive) segment of the industry, and visitors will have a guilt-free vacation [81]. Yet, during the World Congress of Adventure Travel and Ecotourism, just half of the ecotourism product and management claims were backed up by facts, and none of the advertisers made monetary donations to conservation [82]. The fact that few customers comprehend environmental claims and that many of them are unregulated is a major issue. Customers utilize brands and labelling to establish opinions about the environmental soundness of products. However, descriptive information on tourism goods and eco-denominations for tourist products such as green, soft, sustainable, or ecotourism are popular in the tourism sector in the form of quasi-ecological labels [83]. Many of the claims made on goods are unverifiable, ambiguous, imprecise, argumentative, or deceptive, according to the findings.

The only means to formalize an environmental claim is through an independent, impartially conducted environmental award [80]. There is an increasing number of awards that are clearly or indirectly related to the environment as part of quality management. In the service business, identifying and applying quality criteria is unquestionably difficult [84]. In the case of tourism, which has a broad sector of small companies operating in many nations with varying development aspirations and administrative frameworks, the scenario can be considered the same and true. Even in the best-case scenario, attempting to establish industry-wide standards for tourism will result in discrepancies [85]. Environmental quality is seen hardly to be applied within the tourism industry. A different situation occurs for health and safety aspects. The assessment on this issue is clear, and various examples can be adapted from worldwide. Key developing concerns include how to encourage the tourist sector to be environmentally responsible, how and when to make potential customers aware of industries that meet particular criteria, and how to check the accuracy of environmental claims that need to be addressed. One of the approaches that can be applied to relate tourism and the environment in qualitative terms is via awards. The awards given need to satisfy several strict conditions and be thoroughly based on data via secondary sources. The common comparison that is used is made between the approaches on the focus, criteria, certification method, and also results. Awards can be given to stimulate manufacturers or customers, the manufacturing process, the product offered, or the site itself.

Benchmark systems are a natural progression from top performance awards in that they recognize all organizations that achieve a certain level of performance. The Blue Flag Scheme and most ecolabelling schemes are two examples. Benchmark systems are used to grade performance and offer prizes, similar to how hotels are rated from one to five stars. These will, on average, be more expensive than high-performance systems. Another alternative initiative is to reward the organization that poses improvement in their environmental performance. A plan-do-review process needs to be carried to ensure that the organization understands that environmental management is a progressive concept. Organizations that apply for these programs are pledging a long-term commitment to improvement. EMAS, the European Union Environmental Management Audit Plan, is perhaps the greatest example of a continuous improvement scheme. The only way to cover the whole tourism industry, independent of site-specific peculiarities, is to use ISO 14001 and EMAS frameworks that have been developed for the tourist sector. Table 1.10 summarizes the key characteristics of such an award. An EMS offers a wide range of benefits, including a bottom-up approach, flexibility, leadership, and adaptability, as well as a top-down regulatory framework. The EMS necessity to create an internal

Table 1.10 General tourism environmental award

Aspect	Description
Focus	Global environmental management system (EMS) designed for all types and sizes of tourism organizations to accommodate diverse geographical, cultural, and social conditions
Criteria	A continuous environmental cycle of plan do review must be established to include:
	• Environmental policy appropriate to the organization
	• Site/organizational review to establish environmental issues
	• Program of environmental targets
	• Operationalization of program
	• Audit and review of the effectiveness of EMS
Certification	• An organizing body independent of, but supported by, key stakeholders administer the awards
	• Organizations'/sites' EMSs are verified by accredited environmental verifiers, based on documentary evidence and site visit
Result	Global Award/Flag with wide consumer recognition, industry support, and environmental credibility

system for managing the environment necessitates self-awareness and self-help, and environmental considerations are internalized.

To encourage business sectors, we must have a system that takes into account seasonal fluctuations and is also progressive, one that not only pays attention to seasonal changes but rewards excellent waste management by dealing with the cause of pollution on a polluter pays basis [38]. Local governments should collect waste management fees from companies at a greater rate than from homeowners since these industries create more garbage. The waste management fee rate should consequently be a volume-based fee.

1.6.1 Zero-Waste Concept

Many societies and countries have come to recognize the “Zero Waste” concept as an ideal target for long-term waste management. This aids in the creation of a policy that removes landfills and prevents all unsustainable end-of-pipe options such as incinerators. Since waste is a human problem, and waste from any source and in any quantity is a nuisance, zero waste necessitates a mental shift in society. It will not be easy to achieve Zero Waste or even come close to it. “Zero waste” is a rational planning strategy that incorporates concepts of efficient human and material resource management to prevent discards from being waste—an inefficient form—in a way that breathes new life into it the economy of the area [86]. The current world situation is facing various discarded materials and objects that cannot be reused, recycled or compost, which requires the consumer to reduce or look into a different alternative of products. All parties need to participate to ensure that the global production of solid waste can be reduced. Zero waste aims to link the community responsibility and industrial responsibility and eventually to responsible policies and governance [87]. Zero waste combines ethical practice with a sound economic outlook for both local and leading communities. It creates local jobs and creates jobs for companies to collect and process secondary materials and offers companies a new product. On the other hand, the concept is a way to increase their efficiency of product usage. The tourism industry should adopt the concept to ensure that the cost and management could be improvised.

Zero waste should consist of various components, including building relations, society participation, resource recovery, material substitution, and clean production. Tourism industries should consider all the components. Waste is also a symbol of our society’s broken relations. To make rural tourism components viable and sustainable, outsourcing must be stopped to help the local economy. Rebuilding societal relationships and confidence to improve. The circular flow of materials would reduce waste and increase productivity. More business prospects Zero Waste is a method of reducing waste. A place where people can communicate more freely, institutions and neighborhoods. Participation is a crucial component of zero waste. For resource conservation and sustainability, everybody in society should have a place and a position in a zero-waste world. People’s involvement should be ensured in the process, from preparation to execution. In the tourism industry, every party covering authorities, hotel, restaurant, mall, and even tourists should understand their particular role to help reduce the burden of tourism activities. The amount of solid waste production can be reduced by resource recovery via segregation at source, recycling, reusing, repairing, reconstructing, and composting. Material recovery facilities (MRF) are the modern facilities that carry out the sorting, cleaning, storing, and streamlining of the process of the waste. The recycled materials can be used back as a raw material for the reproduction of the same product or other goods. However, the efficient practice that should be implemented is the segregation of waste at the source. The generation of waste at different tourism spots/modes has produced a large amount of waste. Educating the tourist, visitor, and consumer regarding the practice will surely reduce the burden for MRF to be carried out. Furthermore, the management can generate passive income by selling recycled items or hand them over to SWM contractors. During Stockholm Convention, the usage of toxic and unsustainable have been discussed and signed by multiple countries. The verdict of the convention has agreed that the usage of non-environmental-friendly materials should be replaced with local and eco-friendly sustainable materials [88].

1.6.2 Awareness

The awareness among tourists, industries, and community are very important in mitigating the enormous amount of tourism waste. According to a study, awareness had influenced their waste management methods, particularly in terms of segregation, reduction, reuse, and recycling [89]. Initiatives such as encouraging the usage of shopping bags and reusable bags is an alternative to reduce the amount of plastic waste. As a means of limiting the amount of plastic trash generated while international travel, the World Travel and Tourism Council has provided these four suggestions to travellers: bring your water bottle and water treatment system, carry a collapsible bag, decline tiny bottles of toiletries when booking accommodations, and locate places to recycle your plastic trash.

The gap in MSW management practice between occupational groups was most likely due to their awareness of environmental pollution issues and consequences [90]. Outreach and education are critical for managing expectations and promoting recycling compliance. Workplace education with department heads and unions is necessary to guarantee a smooth transition to a sorted solid waste stream from tourism providers. When governments compensate residents for cleaning up road verges and illegal dumping instead of fining violators, the public hears a mixed message regarding trash, illegal dumping, and littering. Solid waste management and recycling education need to be implemented to address food insecurity and poverty.

Aside from awareness, the relationships between beliefs, attitudes, behavioral intentions, and actions in many domains such as advertising, public relations, and advertising campaigns, as well as in healthcare, are equally essential [91]. Promotion and development of indigenous knowledge for visitors to utilize items in study area stores, such as the utilization of traditional baskets, bags, and containers manufactured by the hill tribes to reduce the amount of waste generated. This promotes the goods of the hill tribes and creates revenue for the residents. Additionally, store owners should work with buyers to promote the "refuse plastic bags" campaign and the usage of cloth bags.

1.6.3 Strategic Planning

Collaboration between public and private authorities is vital to convincing the stakeholders and promoting the long-term handling of solid waste. Public-private partnerships (PPP) can be used as an effective tool for the decision-making process and planning. Furthermore, collaborative approaches may help in producing strategic planning (identifying problems, setting direction, and implementing initiatives) using access to infrastructure, networks, financial assistance, training, technical assistance, information sharing, and expertise, which are all possible [92]. The waste and wastewater treatment system, waste management scheme, cultural and natural heritage policies, and social conditions in a destination may all affect the performance's long-term viability. When external factors obstruct changes in sustainability efficiency, collaboration can be required [93]. Engaged and facilitated dialogue can thus lead to a better regulatory and institutional framework based on complementarity, subsidiarity, and neutrality, which can ultimately improve transparency and accountability within the regulatory and institutional framework of the waste management industry [21, 23].

Another popular instrument that can be used to deal with solid waste management is extended producer responsibility (EPR). It is an environmental approach based on the "polluter pays" principle where people who bring packaging or packaging products into the market of a country remain responsible for them until the packaging life cycle is completed. Re-designing and reconceptualize the product design may help to reduce waste generation and move toward a zero-waste target [21]. The scope of the producer's responsibility depends on the model applicable and is usually financial, as well as being organizational in some cases [94]. Companies that market any packaging products must collect, sort and recycle or dispose of the packaging as soon as they have reached the end of their lifetime, in an environmental-friendly manner. Several European countries have adopted EPR in their country, including Germany, Spain, France, and Belgium. Around 2.4 million tonnes of lightweight packaging, some 2 million tonnes of paper/cardboard, and more than 2 million tonnes of glass have been collected by Germany through the EPR system. The production management organization recycles approximately 90% of all packaging in Belgium. It created around 2500 job opportunities on the Belgian market annually and by now. From the waste collection, sorting, and recycling to 56 million tonnes of packaging waste recycled in France, it was able to raise 9.5 million euros for packaging management activities. In conclusion, the organization has recycled 19.3 million tonnes of packaging in Spain since 1998 and has created 42,600 jobs, more than 9400 directly in Spain. It should also be taken into account, in many countries referred to, there are several such approaches and systems to "EPR systems" collectively [95]. EPR is "an environmental policy approach, in which producer responsibility for a product is extended into the post-consumer phase of a product life cycle," declares by the Organisation for Economic Co-operation and Development (OECD) EPR [96]. PR recommends that manufacturers be responsible for collecting, sorting, and treating used goods before possible recycling, as shown in Fig. 1.10.

A specific EPR (System Operator/Producer Responsibility Organization) should be established to transform individual responsibility into collective responsibility. Consequently, the producers and importers responsible for financing and organizing the EPR system shall organize or take responsibility for the system via a predetermined organizational form. The institution system operator referred to. Manufacturers of EPR products should be clearly defined. The OECD states that the "producer" is defined as the entity that exercises the greatest control over the material selection and product design. This could be the brand owner, important or the packaging filler instead of the container manufacturing company. Several SWM parties are involved in tourist regions in Tunisia for ERP setup. The key stakeholders are the municipalities, the private sector, tourism companies, including hotels, the Local Ministry of the Environment, the Tourism Ministries, and the Ministry of Finance. Table 1.11 lists the role and responsibility of the organization in Tunisia to execute ERP and ensure that the system works without any overlapping roles [78].

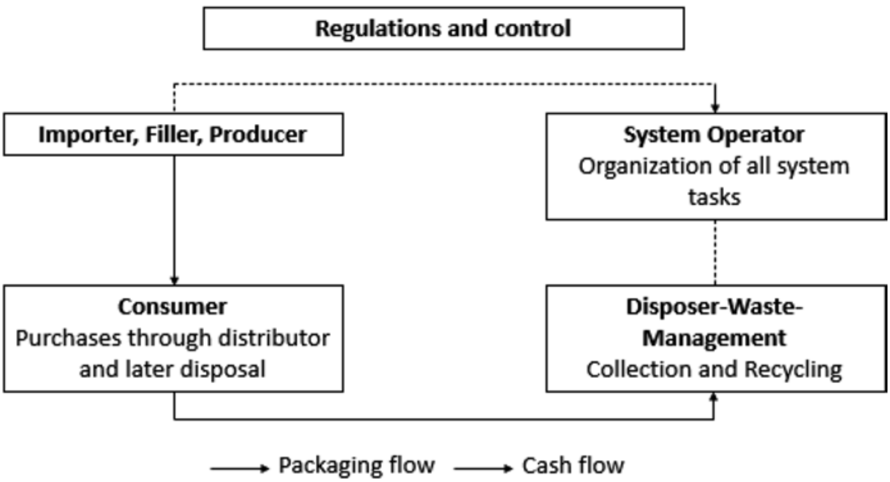

Fig. 1.10 Foundation of the extended producer responsibility (EPR) system for solid waste management development [78]

Table 1.11 Overview of recommended organization and their responsibility [78]

Organization	Responsibility	General
Central government	• National Policy	Policy supervisor and financial supporter
	• Financial support to local government	
ANPE/ANGED/ CITET	• Technical support to hotels	Policy supervisor and technical supporter
	• Control and follow-up of the process	
Local Government	• Formulate policies in concertation with other partners	Policymaker
	• SWM service in the tourism destination	Service provider
Private sector	• Policy partner	Service provider and partner
	• Service provider and operating following the standard	
Society/citizens/ NGOs	• Partner in the SWM process (respecting laws, sorting at source)	Partner and beneficiary
	• Developing pilot projects	
Federation of hotels	• SWM strategy development-main partner	Key partner
	• Coordination and control of the SWM process	
	• Decision-making main partner	
Hotels	• Waste sorting at source	Partner and contributor
	• Support the effort of the municipality (beaches and street cleaning)	
	• Coordination with FTH	

FTH Tunisian Federation of Hotels

1.6.4 Technology and Tools

Technologies and tools are modern alternatives that can provide better improvement for current practices. Technology is defined as modern facilities and high-end equipment that enable a faster and better treatment system. Current technology with high specifications needs a high cost for purchase and maintenance but can provide an efficient result. Incineration is the most common technology used to cater to a massive amount of solid waste. This technique has been widely employed in highly industrialized nations over the last 50 years, and it can reduce the volume of garbage that is landfilled by roughly 75% by weight and 90% by volume. However, there are still few other options available and may suit the waste generated as different regions generate different compositions of waste. Centralized mechanical treatment (MT) and mechanical/biological treatment (MBT) plants, as an example, are two other treatments that can be utilized for biodegradable waste. Several other alternatives of biological treatment that can be found in MBT includes anaerobic treatment (fermentation), aerobic treatment, or utilizing biological treatment using the principles of bio-drying [10]. Sewage generated also should be properly addressed by biochemical treatment or even composting. Thermal processes can opt for the treatment of sludge, for example.

The tool is a concept, approach, or modelling that can be used to develop and forecast the future status of the environment. Various tools have been developed to assist the assessment of waste management. The authors have summarized several tools (Table 1.12) from the literature review that are effective and can be used as an indicator to determine the current and future status of the environment especially waste management.

1.6.5 Regulations

Strict enforcement and high fines could reduce the amount of waste generated and educated the community, including tourists. In some cases, the tourist does not even care to dispose of their waste properly due to their short stays, no sense of responsibility, and poor management itself in that place. Tourists often express free-rider behavior compared to the local population as they do not have any social ties [8, 103]. Different waste source falls under different standards and guidelines that are unique according to a country, region, or worldwide standard. The authors have summarized the available standards/guidelines in Table 1.13 [25].

Cruise has been considered as one of the potential polluters either on the ocean or land. Thus, for that reason, a specific standard is required together with several guidelines and agreements via a convention. Overall, the Helcom Standard covers the legislation on the release of wastewaters into the Baltic Sea, while the MARPOL

Table 1.12 Several tools for environmental monitoring and modelling

Tools	Descriptions	Reference
Tourism Environmental Carrying Capacity (TECC)	• Described the relationship between tourists and the natural environment they visit.	[30, 97–99]
	• Evaluating an environment's ability to accept people, which included three primary aspects: social, economic, and environmental status	
	• Denoted the maximum population that can consume a region's resources without causing unacceptable degradation while maintaining a pleasant recreational experience.	
Geographic Information System (GIS)	• Assess the land use planning following sustainable urban development.	[75, 100]
	• Assessing the environmental impact along with mapping and mathematical models	
STIRPAT Model	• Assisting public authorities in gaining a better understanding of the relationship between visitor growth and garbage generation, as well as contributing to proper policymaking in mature tourist locations.	[101]
Multiple Linear Regression (MLR)	• Use to quantify organization MSW and contribute to the development of the current unsuitable management system for MSW resulting in a reduction in the negative environmental impact created by the certain sector.	[102]

Table 1.13 Summary of some of the standards/guidelines based on different waste sources [25]

Waste source	Act/standard/guidelines/convention	Reference
Cruise	• Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention)	[30, 50]
	• International Convention for the Prevention of Pollution from SHIP (MARPOL Convention)	
	• The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention)	
Mainland/ Island	• Waste Framework Directive (WFD)—Directive 2008/98/EC of the European Parliament	[104–107]
	• National acts/regulations for each country	
	Example:	
	– Malaysia Solid Waste and Public Cleansing Management Act 2007 (Act 672)	
	– South Africa Waste Act 2008	
	– Australia Waste Policy	

convention includes the prevention of pollution by ships (waste wasters, solid waste, oils, and air pollution). One hundred fifty-six states of the world have agreed under the MARPOL Convention, which covers almost 99.42% of the world fleet. MARPOL is broken into several subcategories (Annexes) as shown in Table 1.14, each of which is broken down to a specific set of ship pollutants. Wastewater management systems, disinfection equipment, and storage tanks are all required aboard ships. Untreated waters can only be released when they have undergone a densification procedure at more than 3 nautical miles from the nearest land. In the event of entirely untreated wastewaters, the distance from the nearest land must be greater than 12 nautical miles, with a regulated discharge speed and a sailing speed of at least 4 knots. At all places, wastewater can be released through an approved management system if there are no visible particles or color changes in the surrounding sea. The most serious issue is non-dissolvable and poisonous compounds. Plastics, synthetic ropes, incinerator ashes, cooking oil, paper, metal components, and bottles of any sort, and similar things are prohibited for disposal into the sea. Food waste, nontoxic sanitary compounds, and animal corpses are examples of waste that can be released. In the Antarctic Sea, the presence of large vessels could damage the ecosystem, especially when the small vessel is considered not economical enough to operate in this area. However, under the International Convention for the Prevention of Pollution from Ship, the use and carrying of heavy and intermediate fuel oils for ships was prohibited in the Antarctic Sea [30].

Consumer laws should be enforced to protect the right of tourism shoppers locally and abroad [108]. Law enforcement is important to prevent any deception for products specification and price, warranty period, and mostly gain the shopper trust especially when they are from abroad. Customers can purchase confidently due to high-security protection and can obtain legal advice if anything happens.

The polluter pays principle is a realistic concept that can be regulated. The tourist or resident should be responsible for the waste they generate. Implementing the

Table 1.14 Summarization of MARPOL Convention and the year of the Annex enforced [59]

	Year	Regulations	Description
Annex I	1983	Regulations for the Prevention of Pollution by Oil	Covers prevention of pollution by oil from operational measures as well as from accidental discharges. 1992 amendments made it mandatory for new oil tankers to have double hulls and brought in a phase-in schedule for existing tankers to fit double hulls, which was subsequently revised in 2001 and 2003.
Annex II	1983	Regulations for the Control of Pollution by Noxious Substances in Bulk	Details the discharge criteria and measures for the control of pollution by noxious liquid substances carried in bulk. No discharge of residues containing noxious substances is permitted within 12 miles of the nearest land.
Annex III	1992	Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form	Contains general requirements for the issuing of detailed standards on packing, marking, labelling, documentation, stowage, quantity limitations, exceptions, and notifications.
Annex IV	2003	Prevention of Pollution by Sewage from Ships	Contains requirements to control pollution of the sea by sewage; the discharge of sewage into the sea is prohibited, except when the ship has in operation an approved sewage treatment plant or when the ship is discharging comminuted and disinfected sewage using an approved system at a distance of more than 3 nautical miles from the nearest land; sewage which is not comminuted or disinfected has to be discharged at a distance of more than 12 nautical miles from the nearest land.
Annex V	1988	Prevention of Pollution by Garbage from Ships	Deals with different types of garbage and specifies the distances from land and how they may be disposed of; the most important feature of the Annex is the complete ban imposed on the disposal into the sea of all forms of plastics.
Annex VI	2005	Prevention of Air Pollution from Ships	Sets limits on sulfur oxide and nitrogen oxide emissions from ship exhausts and prohibits deliberate emissions of ozone-depleting substances. A chapter adopted in 2011 covers mandatory technical and operational energy efficiency measures aimed at reducing greenhouse gas emissions from ships.

"polluters pay" approach could help to reduce trash generation by the public and, as a result, reduce management expenses, notably garbage collection expenses.

1.7 Conclusion

Tourism waste is demanding more attention and action. This chapter has gone into detail about the source of waste in the tourism industry and the implication on the environment, economy, and finance. Furthermore, a collaborative partnership between stakeholders, tourism players, government and private sectors could boost efficient waste management. Implementing best practices and technical controls at the tourism facility will help to mitigate the waste. Strict law enforcement and utilizing available tools could help the authorities to forecast the tourism waste generation and plan for future planning.

Glossary

Aerobic Composting A method of composting organic wastes that involve the use of bacteria that require oxygen. This necessitates exposing the waste to sunlight, either by turning it or pushing air into pipes that pass through it.

Bioaccumulation Accumulation of toxic substances within living organisms contributed by the environment.

Biodegradable A decaying process due to nature.

Biodiversity Diversity among and within plant and animal species in an environment.

Biotic Pressure Stress that occurs due to damage done to an organism by other living organisms.

Convention An international agreement reached for a specific matter.

Ecotourism Tourism directed toward exotic, often threatened, natural environments, intended to support conservation efforts and observe wildlife.

Environment Footprint The effect that the environment received due to the consumption of natural resources and the by-product produced, such as harmful gases generated.

Extended Producer Responsibility Environmental protection strategy that makes the manufacturer of the product responsible for the entire life cycle of the product and especially for the take-back, recycling, and final disposal of the product.

Glacier An extended mass of ice formed from snow falling and accumulating over the years and moving very slowly.

Gross Domestic Product (GDP) Measurement that seeks to capture a country's economic output. Countries with larger GDPs will have a greater amount of goods and services generated within them and will have a higher standard of living.

Landfill An engineered method of disposing of solid waste on land that meets most of the standard requirements, such as proper siting, comprehensive site planning, proper leachate and gas management and tracking, compaction, regular and final cover, full access control, and record-keeping.

Material Recovery Facility A facility for manually or mechanically separating commingled recyclables. Some MRFs are planned to distinguish recyclables from mixed municipal solid waste. The recovered materials are then baled and sold by MRFs.

Pastures Land covered with grass and other low plants.

Repercussion An unintended consequence of an event or action, especially an unwelcome one.

Snowlines The altitude in a particular place above which come snow remains on the ground throughout the year.

Solid Waste Any material that is discarded.

Vacuum Collection System An automated waste collection system which conveys waste by air suction from individual buildings through a network of pipes to a central location for collection.

VOC Volatile organic compound. Gases that are emitted from certain solids or liquids that may have short- and long-term health effects.

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Chapter 2
Rubber Tire Recycling and Disposal

Noor Ainee Zainol, Ahmad Anas Nagoor Gunny, Hamidi Abdul Aziz, and Yung-Tse Hung

Abstract Waste management is an important indicator for creating sustainable and livable cities, but it remains a challenge for many countries around the world. Millions of rubber tire waste pollute the environment due to improper disposal methods, creating a global environmental crisis. The number of rubber tire waste piles continues to grow, posing greater environmental, safety, and aesthetic issues due to a lack of clear disposal options. This chapter gives a general overview of rubber tire waste recycling and disposal worldwide. A brief history of natural and synthetic rubber and global rubber production and consumption was first discussed. Next, various rubber tire recycling and disposal technologies were elaborated. This is followed by discussing the issues involved in recycling and disposal.

N. A. Zainol (✉)
Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Padang Besar, Perlis, Malaysia

Centre of Excellence Water Research and Environmental Sustainability Growth (WAREG), Universiti Malaysia Perlis (UniMAP), Arau, Perlis, Malaysia
e-mail: aineezainol@unimap.edu.my

A. A. N. Gunny
Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Padang Besar, Perlis, Malaysia

Centre of Excellence for Biomass Utilization (COEBU), Universiti Malaysia Perlis (UniMAP), Arau, Perlis, Malaysia
e-mail: ahmadanas@unimap.edu.my

H. A. Aziz
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Solid Waste Management Cluster, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: cehamidi@usm.my

Y.-T. Hung
Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, OH, USA
e-mail: y.hung@csuohio.edu

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Acronyms

BDS	Broadband dielectric spectroscopy
dBA	Decibel
DMA	Dynamic mechanical analysis
ELTs	End-of-life tires
EPDM	Ethylene-propylene-diene monomer
EPR	Extended producer responsibility
GTR	Ground tire rubber
HHV	Calorific value
NR	Natural rubber
OTR	Off-the-road tires
SBR	Styrene-butadiene rubber
TDF	Tire-derived fuel
USEPA	United Sates of Environmental Protection Agency
USTMA	United States Tire Manufacturers Association

2.1 At a Glance: A General Picture of Solid Waste Generation and Management

Solid waste has recently emerged as a major issue in our society. The term “solid waste” refers to a material deemed worthless by its producers, while pollution refers to any change to the natural environment. Solid waste is generated in a given area as a result of industrial, residential, and commercial activities and can be handled in a variety of ways.

The generation of solid waste is frequently associated with economic growth and development, and its impact on people and the environment is a global concern. Such expansion has altered consumption patterns and lifestyles, as well as raised the general public’s standard of living. These changes have resulted in massive waste generation, which shows no signs of abating. Figure 2.1 depicts the global amount of municipal solid waste generated in 2016, along with projections for 2030 and 2050. It is estimated that the world will generate 3.4 billion metric tons of solid waste.

To ensure environmental best practices, solid waste must be managed systematically, regardless of its origin, content, or hazard potential. Solid waste management is a critical component of environmental hygiene and must be considered in environmental planning. In general, solid waste management entails the regular collection, transportation, processing, disposal, recycling, and monitoring of various types of waste materials.

The most fundamental concept in waste management is waste hierarchy (Fig. 2.2). It refers to the “3Rs” of waste management strategies, which classify

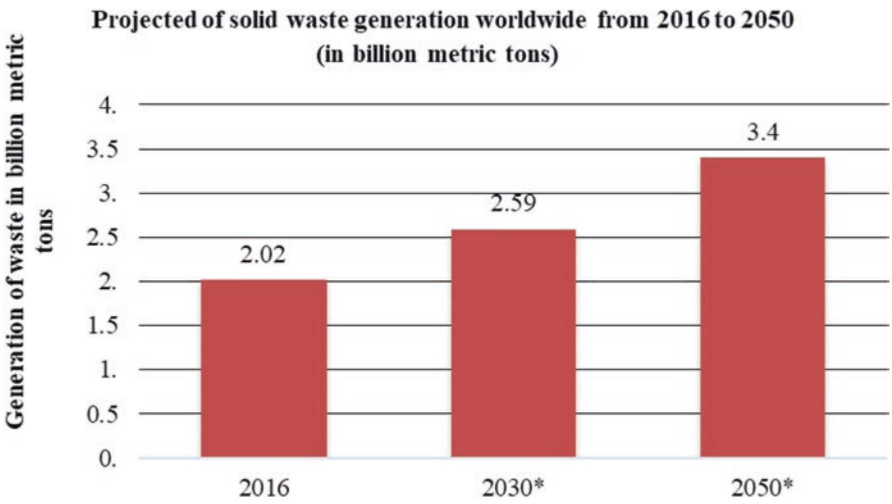


Fig. 2.1 Global municipal solid waste generation projection 2016–2050. (Source: World Bank [1])

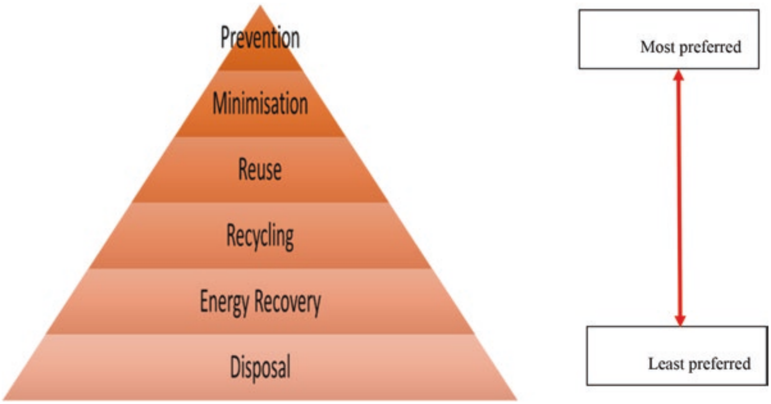


Fig. 2.2 Waste hierarchy

waste management strategies based on their desirability for waste minimization. Most waste reduction strategies still rely on the waste hierarchy. The goal of the waste hierarchy is to extract the most useful benefits from products while producing the least amount of waste.

In general, this chapter focuses on rubber tire waste in general, as well as recycling and disposal options. Rubber tire waste is classified as solid waste. It is critical to understand that tires eventually become waste and can no longer be used for their intended purpose. Rubber tires are difficult to dispose of due to the complex ingredients that make them safe, and the problem is getting worse by the year. It is a difficult task because rubber tire waste is non-biodegradable and lasts for long periods of time. The traditional method of disposing of rubber tire waste was stockpiling, illegal dumping, or landfilling, all of which are temporary solutions. Whole tires, in general, are difficult to landfill because they tend to float to the surface. Many communities have scrap tire stockpiles, causing public health, environmental, and aesthetic issues.

2.2 Brief History of Natural and Synthetic Rubber

Natural rubber originated in Central America. Rubber was known to the indigenous peoples of the Americas long before European explorers arrived. It is primarily harvested in the form of the latex from Amazonia rubber trees (Hevea brasiliensis). The indigenous people of Mesoamerica were the first to use rubber. People in Mexico and Central America were harvesting and using natural rubber in liquid form for medicinal purposes and painting as early as 3500 years ago.

During the second half of the nineteenth century, natural rubber underpinned one of the most significant development booms in Brazil. At the time, the Industrial Revolution was rapidly spreading as the world experienced a period of prosperity and discovery that was reflected in all sectors. As automobiles became more popular in the early twentieth century, there was an increase in demand for tire and rubber products. Massive rubber plantations were also established throughout Asia, most notably in Malaysia, Ceylon, and Singapore.

World War I and II altered the landscapes of the rubber industry worldwide. The decline in natural rubber production in Brazil coincided with World War I (1914–1918) due to Japanese conquests of Asia's plantations. This gives pressure for producing lower-cost products with more consistent supplies in order to manufacture tires as well as to fulfil the high military demand at that time.

Again, during World War II (1939–1945), the United States was unable to supply rubber globally and was forced to develop methods of producing synthetic rubber in order to meet high wartime demands. Butadiene, the first synthetic rubber, was developed in 1910 and became popular during World War I due to natural rubber shortages. Natural rubber became available again after the war, and synthetic rubber was not in demand again until the 1960s.

Rubber has been used by humankind for thousands of years. Rubber is an organic compound composed of unsaturated carbon and hydrogen. It comes in two types, namely natural and synthetic. Latex from the rubber tree is vulcanized, pigmented, finished, and modified into a variety of commercially viable products. Natural rubber is widely used in a variety range of applications and products, the most well-known of which are tires. It has a high stretch ratio, resistant to water and chemical interactions, and does not conduct electricity, making it versatile for a wide range of applications.

Both types of rubber outperform the other in some areas, but natural rubber's beneficial properties outweigh synthetic rubber's performance. The advantage of synthetic rubber, which refers to any artificial elastomer, is that it is easier to produce than natural rubber. Natural and synthetic rubber were both in use at the end of the twentieth century.

2.3 Global Rubber Production and Consumption

Because this plant grows only in warm, damp regions near the equator, the countries of South-East Asia that account for 90% of true rubber production are Malaysia, Thailand, and Indonesia. However, significant changes redistributed production among the main competitors. Malaysia, which accounted for one-third of global output in 1985, has fallen behind due to changes in its production profile, which has begun to emphasize non-agricultural investments. Thailand is now the world's largest producer of natural rubber. Thailand's production record for 2019 alone indicated a total of 4852 metric tons of rubber produced.

Natural rubber production in the world amounted to more than 13.6 million metric tons in 2019. This is a significant increase from the year 2000 when the world produced approximately 6.8 million metric tons of natural rubber. Figure 2.3 depicts global natural production from 1990 to 2019. The Asia Pacific produced 91% of the world's natural rubber in 2018 or 12.64 million tons. Europe, the Middle East, and Africa came in second place, producing 6.5% of the world's natural rubber. Figure 2.4 depicts the total global synthetic rubber production from 2000 to 2019. Globally, approximately 10.9 million metric tons of synthetic rubber were produced in the year 2000. The Fig. 2.4 for 2019 was 15.13 million metric tons. Tables 2.1 and 2.2 show global natural and synthetic rubber production by region, while Table 2.3 shows the top natural rubber producing countries from 2014 to 2018.

Natural rubber consumption accounted for roughly 40% of total rubber consumption worldwide by 2001. With 5.5 million metric tons consumed in 2019, China is by far the largest consumer of natural rubber. That year, India finished a

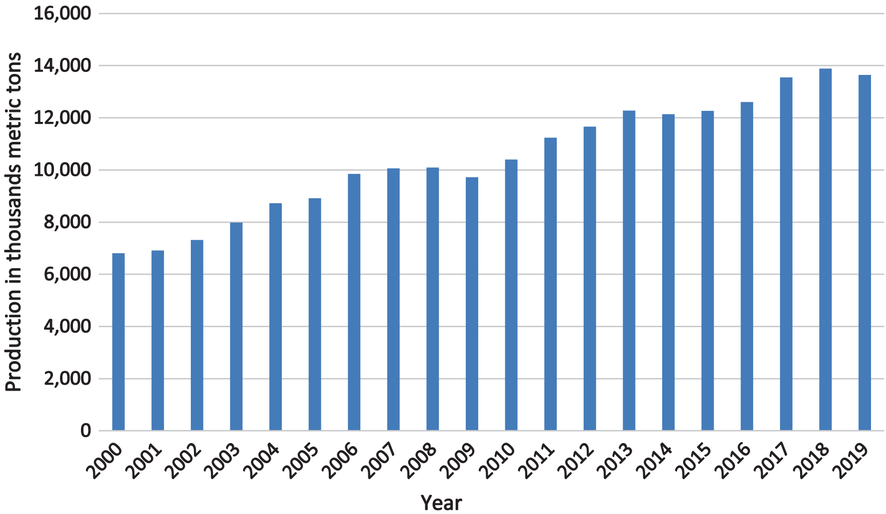


Fig. 2.3 Global natural rubber production from 1990 to 2019. (Source: International Rubber Study Group [2])

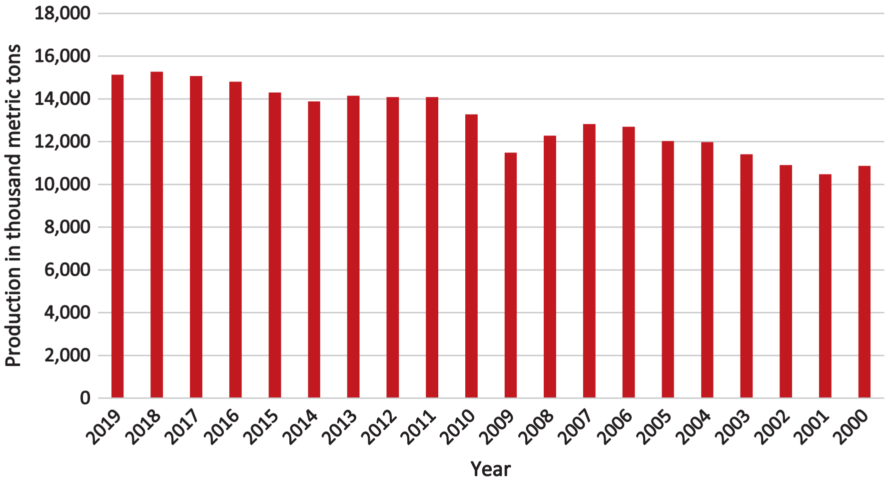


Fig. 2.4 Global synthetic rubber production from 1990 to 2019. (Source: International Rubber Study Group [2])

Table 2.1 Global natural rubber production by region 2014–2018 (in thousand tons)

Region	Year				
	2014	2015	2016	2017	2018
Asia Pacific	11,236	11,340	11,563	12,352	12,644
Europe, Middle East, Africa	564	597	721	867	901
Americas	335	334	320	332	339

Source: International Rubber Study Group [3]

Table 2.2 Global synthetic rubber production by region 2014–2018 (in thousand tons)

Region	Year				
	2014	2015	2016	2017	2018
Asia Pacific	7321	7508	7672	8399	8588
Europe, Middle East, Africa	3887	3914	4137	3861	3889
Americas	2970	3085	3033	2934	2950

Source: International Rubber Study Group [3]

distant second (see Table 2.4). Both countries, particularly India and China, have been successful in expanding in this sector by utilizing their low-cost labor forces and readily available lands. Rubber is used to make latex products, footwear, engineering, belting and hoses, and a variety of other items. The majority of natural and synthetic rubber consumed by the global automotive industry is used to make tires and tubes for vehicles. In general, 13.7 million metric tons of natural rubber and 15.3 million metric tons of synthetic rubber were consumed globally in 2019 (Fig. 2.5).

Table 2.3 World-leading natural rubber producer countries 2018–2019 (in thousand tons)

Country	Year	
	2018	2019
Thailand	4973	4852
Indonesia	3630	3301
Vietnam	1142	1185
China	818	813
India	660	702
Malaysia	603	640
Others	1442	1394

Source: International Rubber Study Group [2]

Table 2.4 World-leading natural rubber consuming (in thousand tons)

Country	Year			
	2014	2016	2018	2019
China	4760	4982	5504	5497
India	1015	1033	1220	1144
United States	932	932	987	1006
Thailand	541	650	752	800
Japan	709	676	706	714
Indonesia	540	583	618	625
Malaysia	447	486	515	501
Brazil	–	412	398	400
South Korea	402	381	367	354

Source: International Rubber Study Group [3]

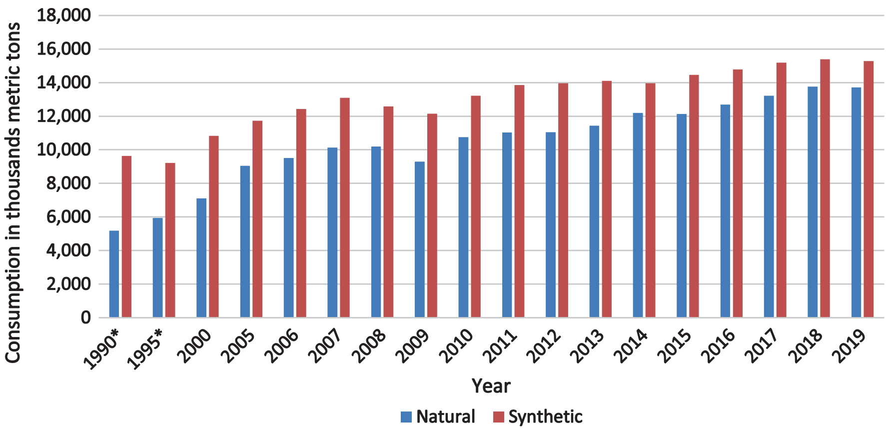


Fig. 2.5 Consumption of natural and synthetic rubber worldwide from 1990 to 2019. (Source: International Rubber Study Group [2])

Figures 2.6 and 2.7 show the main production systems for natural and synthetic rubber, respectively. More than 75% of the rubber produced today is a synthetic product derived from crude oil. Although synthetic rubber can be obtained in a

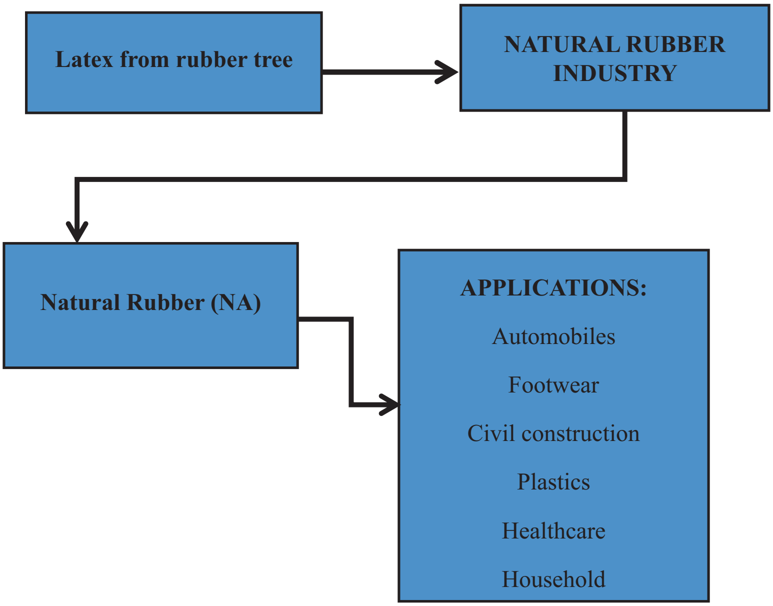


Fig. 2.6 Main natural and synthetic rubber production system

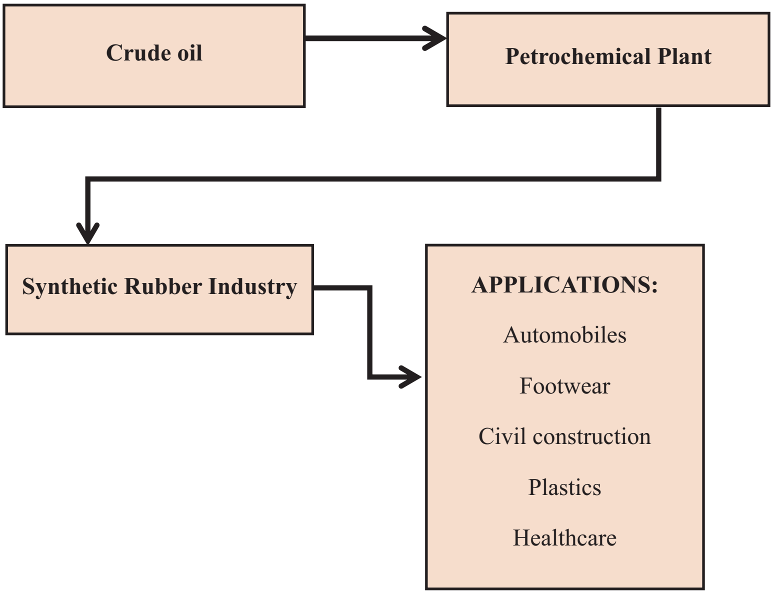


Fig. 2.7 Main synthetic rubber production system

variety of ways, such as butyl, styrene, nitrile, and others, the use of natural and synthetic rubber is critical in almost all economic sectors.

A wide variety of synthetic rubbers have been developed since the discovery of this product. Manufacturing technology was heavily concentrated in long-established global enterprises such as DuPont, Bayer, Shell, BASF, Goodyear, Firestone, Michelin, EniChem, Dow, and Exxon due to the large investments required to develop these various synthetic products. Rubber is widely used because the properties and characteristics of these elastomers make them suitable for automotive, household, industrial, footwear, civil construction, plastics, healthcare, and other critical applications in society's daily life.

2.4 Background of Rubber Tire Recycling and Disposal

Rubber is a type of polymer that is extremely beneficial to humans. It is a very important material in many applications due to its unique and impressive properties. Figure 2.8 depicts some of the unique properties and characteristics of rubber.

Natural rubber (NR), styrene-butadiene rubber (SBR), nitrile, ethylene-propylene-diene monomer (EPDM) rubber, fluorocarbon rubber, and other types of rubber are commonly available [4]. Table 2.5 shows some of the applications for different types of synthetic rubbers. Rubber waste products include scrap tires, inner tubes, discarded and rejected rubber gloves, balloons, rubber bands, shoe soles, mattresses, hoses, seals, gaskets, diaphragms, and others.

Table 2.6 depicts the global amount of waste rubber that is reused, recycled, recovered, disposed of, or stockpiled [4]. Because they are most commonly used to make tires, the styrene-butadiene and polybutadiene varieties of synthetic rubber are the most widely consumed. Waste tires are a problem because of the large volume produced and because they are difficult to dispose of due to their durability. Tons of waste tires pose a global environmental risk due to improper disposal methods, polluting the environment.

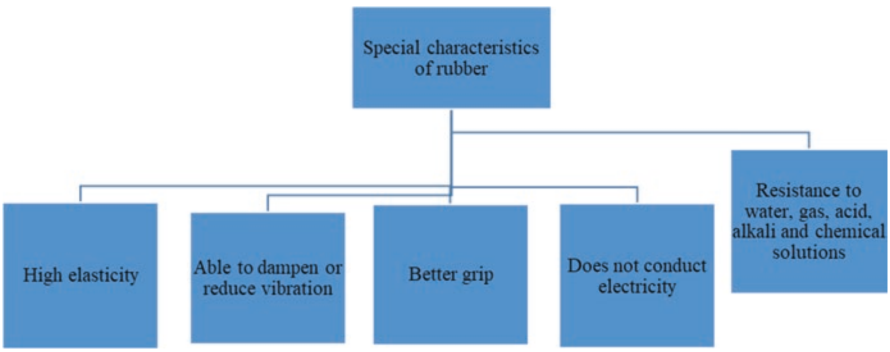


Fig. 2.8 Characteristics and properties of rubber

Table 2.5 Main types and applications for synthetic rubbers

Name	Type of rubber	Adhesives	Asphalt modifications	Footwear	Technical goods	Tires	Treads	Plastic modifications
BR	Polybutadiene	–	–	x	x	x	x	x
CR	Polychlorophene	x	x	x	x	–	–	–
eSBR	R Styrene-Butadiene in emulsion	x	–	x	x	x	x	–
sSBR	Styrene-Butadiene in solution	x	x	x	x	x	x	–
EPDM	Ethylene-propylene	–	x	–	x	x	–	x
Latex	Various types of latex	–	x	x	x	x	–	x
NBR	Nitrile	–	–	x	x	–	–	x
TR	Plastics	x	x	x	–	–	–	x
IIR	B Butyl	x	–	–	x	x	–	–

Table 2.6 Global estimation of waste rubber management

Type	Estimated amount (%)
Recovery (energy)	25–60
Landfill/stockpiled	20–30
Reused	5–23
Recycled	3–15

Source: Forrest [4]

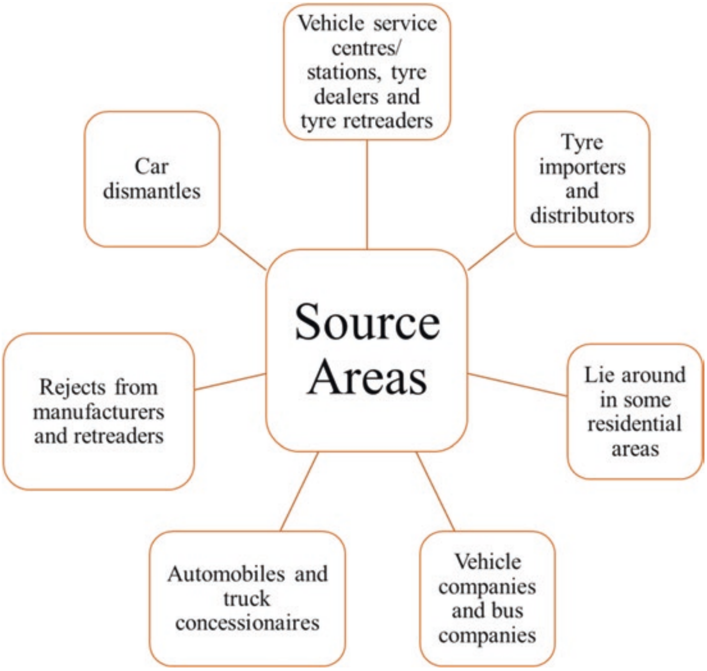


Fig. 2.9 Common source areas of tires that contribute to waste generation

The tires are primarily constructed of rubber. Rubber is a complex compound composed of elastomers, polyisoprene, polybutadiene, and styrene-butadiene. When the casing of a tire wears out, it is either retreaded or discarded. Figure 2.9 depicts the most common waste tire accumulation areas. Essentially, all of the sources mentioned providing information about areas that have difficulty disposing of large amounts of waste tires.

The remarkable increase in the number of vehicles and automobile industries worldwide has given rise to global tire waste generation. Figure 2.10 represents cars sold worldwide between 2010 and 2021. However, the automobile industry experienced a downward trend in the year 2020 as a result of the slowing global economy and the emergence of the coronavirus pandemic in all major economies. Thus, the

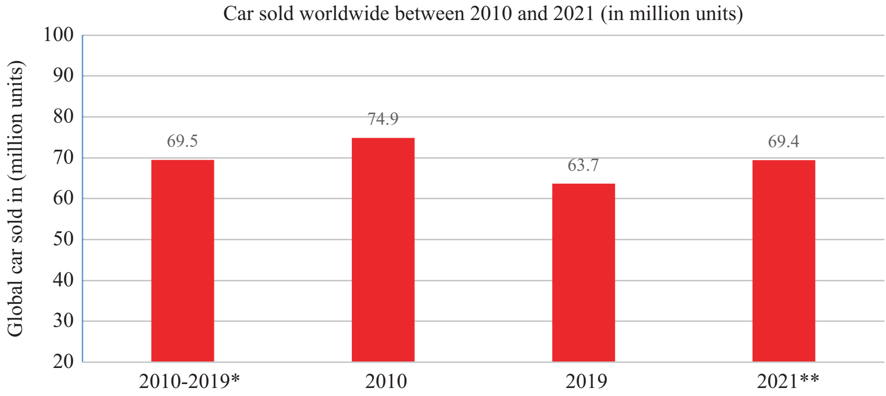


Fig. 2.10 Cars sold worldwide between 2010 and 2021. (Source: Scotiabank; Ward's; Bloomberg [5])

Table 2.7 The volume of scrap processed in the United States

Waste	Volume of scrap (in 1000 metric tons)
Aluminum	5462
Copper	1783
Electronics	5500
Iron and steel	72,400
Lead	1349
Paper	47,800
Plastics (PET bottles)	782.9
Tires	116,000
Zinc	72

Source: ISRI [9]

global expansion of the automobile industry as well as the increasing use of automobiles as the primary mode of transportation have greatly increased tires production.

Once the tire is no longer being served its original purpose and discarded, this type of tire is considered a scrap tire. Rubber tire waste is a significant waste that has been a source of concern for the environment. An estimated 1.5 billion scrap tires annually were discarded worldwide due to the remarkable increase in vehicles on the road [7, 8]. Table 2.7 shows the volume of scrap tire processed for various waste in the United States in 2018, and it was reported scrap tires is the highest around 16,000 metric tons.

Meanwhile, Table 2.8 shows the scrap tire production recorded in the selected countries and their respective per capita data scrap tires in 2012 [10]. Among the selected countries, Japan showed the highest production of scrap tires per capita while Turkey recorded the lowest production of scrap tires per capita in 2012. It was

Table 2.8 Production of scrap tires (per tons) in 2012 among the selected countries

Country	Scrap tires production (per tons)	Per capita
Germany	605,000	7.44
Iran	335,339	4.40
France	416,000	6.34
UK	363,000	5.76
Turkey	261,000	3.52
Spain	280,000	5.95
Japan	1,010,000	7.93
Italy	403,000	6.76

Source: Zarei et al. [10]

reported that approximately 400,000–600,000 tons of tire wastes are produced in Thailand [11], while more than 112 million tire wastes are produced in China [12]. Meanwhile, more than 11 million units of end-of-life tires (ELTs) are produced in South Africa [13]. In the 2013–2014 period, Australia disposed of approximately 408,000 tons of waste tires [14].

However, as Global Recycling [15] reported, this value has decreased thanks to a recycling program that suggests the scrap tires usage in various industries, including building and road pavement [16]. The previous study has proven that one of the effective ways to manage and minimize the accumulation of this waste is through recycling. In general terms, recycling scrap tires involves a recovery of the raw material used for other purposes. USEPA has categorized three types of fields that can benefit from the scrap tires: tire-derived fuel, civil engineering applications, and ground rubber applications such as rubberized asphalt.

The involvement of USEPA was due to the problem resulting from the accumulation of scrap tires, such as the breeding places for insects, which has led to various types of health problems. Other than that, the open burning of scrap tires which generates toxic fumes such as sulfur dioxide, carbon monoxide, nitrogen oxides, and the distribution of carbon particles in the air, was discovered to be posing a serious threat to the environment [17, 18]. Figure 2.11 shows an example of a theoretical framework of solid waste (SW) mismanagement, including the scrap tires illustrated by [19].

This problem has led to the development of two immediate actions by the responsible organization; first is law enforcement and regulation concerning the management of scrap tires. Secondly, it creates a lot of enthusiasm and activity for new recycling activities, including improving the existing technology [20–22]. Figure 2.12 below shows a tire's life cycle illustrated by USEPA, which generalized how the tires have been managed.

Among the 51 countries, WBCSD [24] evaluated tires are recovered at approximately 67%—outpacing glass, aluminum, cardboard, and paper. Furthermore, regional recovery rates for end-of-life tires at the global level are stated in the following Table 2.9.

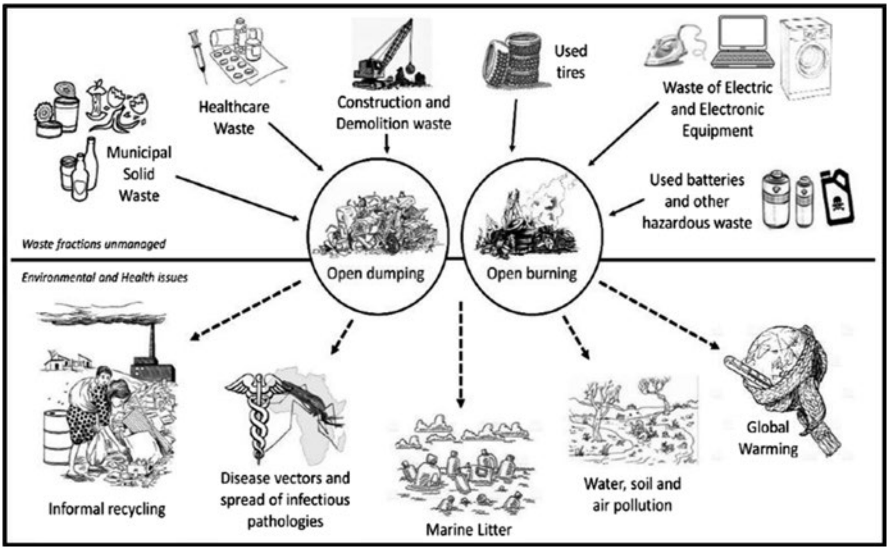


Fig. 2.11 The theoretical framework for a source of contamination due to solid waste mismanagement. (Source: Ferronato and Torretta [19])

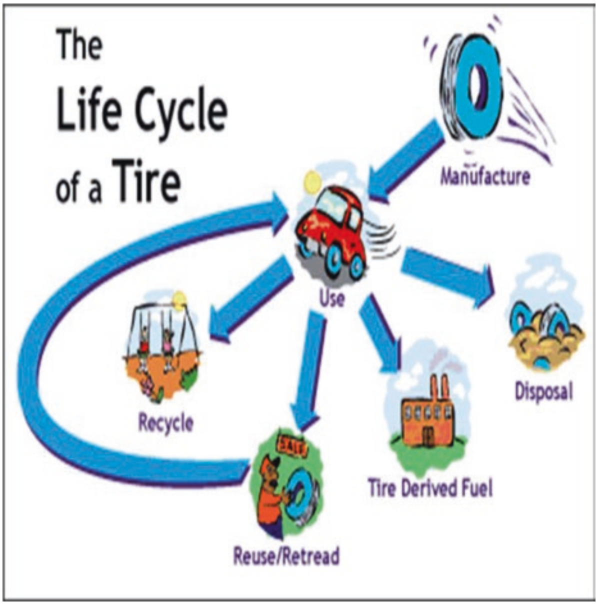


Fig. 2.12 Illustration of the life cycle of the tire. (Source: USEPA [23])

Table 2.9 Regional recovery rate for end-of-life tires

Regional	Recovery rate (%)
Europe	91
United States	87
South Korea	95
Japan	85

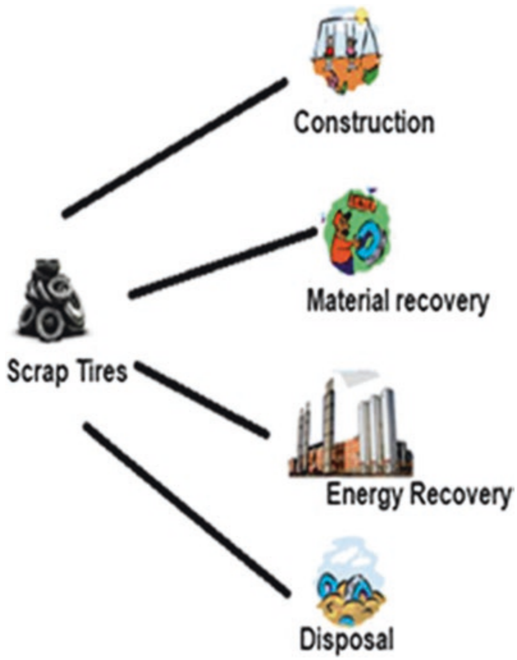


Fig. 2.13 General recycle activities of scrap tires. (Source: USEPA [25])

Some waste products are given new life through reuse or recycling programs as waste management becomes an increasingly important global issue. Every year, scrap tires are converted into new materials, fuels, and reclaimed rubber, all of which help the tire industry build a circular economy. Scrap tires can be recycled into a variety of forms and applications, including construction work and civil engineering applications, material recovery, energy recovery, or they can be landfilled or stockpiled (Fig. 2.13). Table 2.10 shows the annual amount of various goods recovered for recycling from municipal solid waste (MSW) in the United States. In 2014, approximately 2.25 million tons of tires were recovered from MSW. Figures 2.14 and 2.15 depict the recycling rate and volume of tire recycling in South Korea from 2018.

Table 2.10 Various goods recovered from municipal solid waste in the United States for recycling in 2014

Type	Recovery (million tons)
Batteries, lead-acid	2.81
Carpets and rugs	0.21
Furniture and furnishings	0.1
Major appliances	2.71
Miscellaneous durables	1.64
Rubber tires	2.25
Small appliances	0.12
Total durable goods	9.75

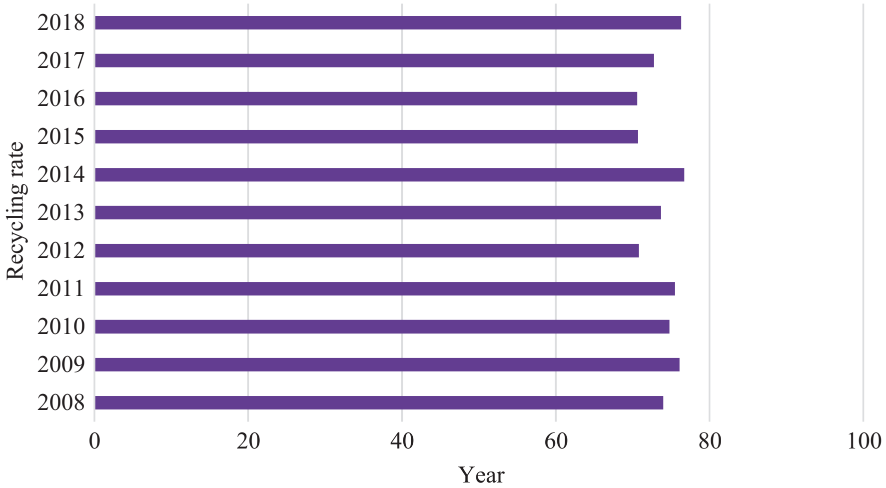


Fig. 2.14 Waste tire recycling rate in South Korea 2008–2018. (Source: ME (South Korea) [126])

Expired tires were recycled and recovered on a global scale, including around 47% for material recovery, 20% for energy recovery, and only 2% for construction materials. Meanwhile, 47% that remain unutilized are not recovered. These waste tires were disposed of either to landfill, stockpiled or illegally dumped or categorized as unknown as shown in Fig. 2.16 [24]. Tables 2.11 and 2.12 show the volume of end-of-life tires collected for recovery and amount of industry revenue from the refurbishment of used tires in Italy and Brazil, respectively.

It was recorded that scrap tires have been added value and utilized in various industries and areas through recycling technology. The summary of its application in building construction industries, rubber pavement industries, automotive industries, geo-technological engineering works, energy generations, and environmental remediation (adsorbents) is depicted in Table 2.13.

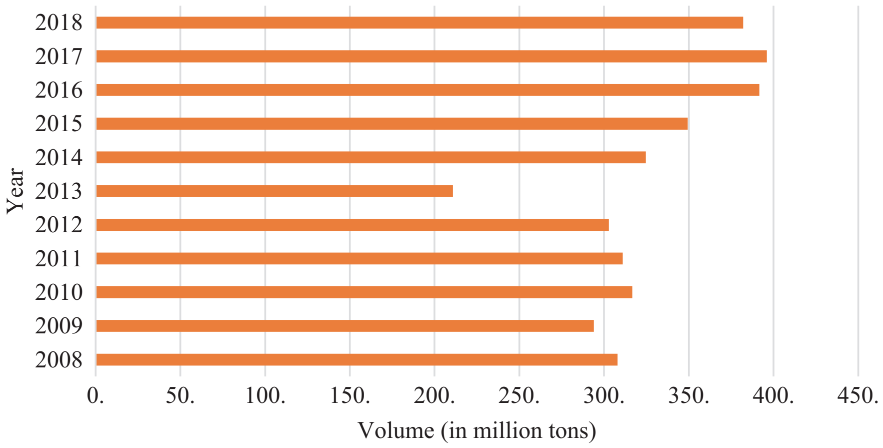


Fig. 2.15 Waste tire recycling volume in South Korea 2008–2018. (Source: ME (South Korea) [127])

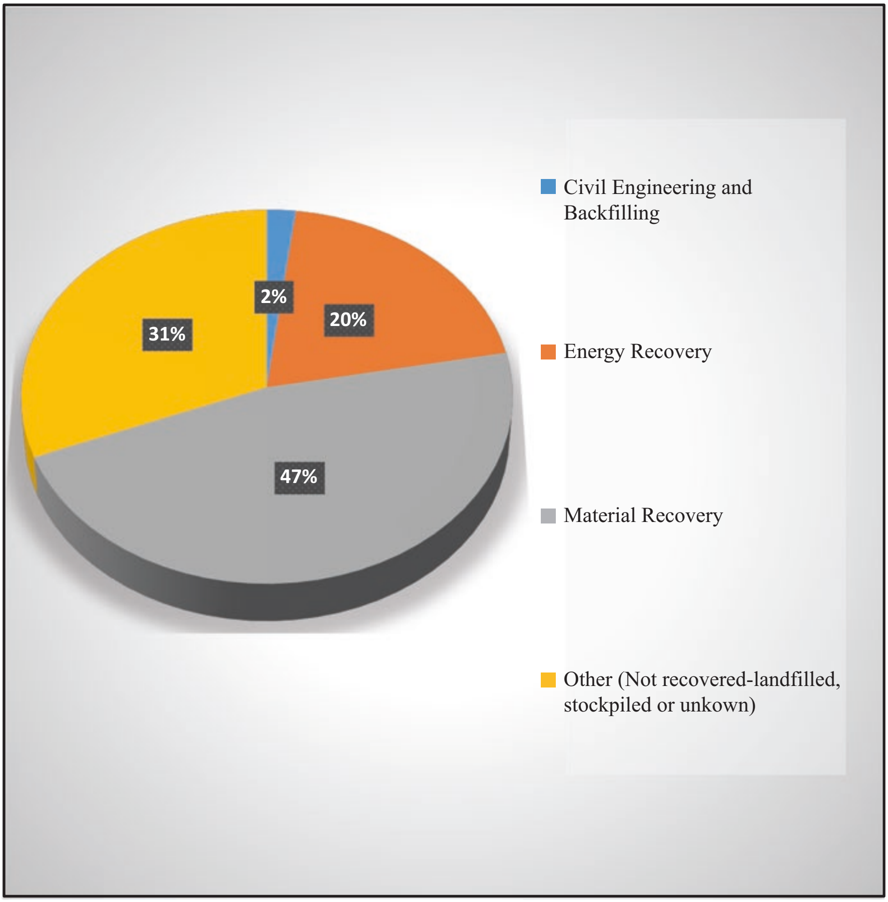


Fig. 2.16 Global total end-of-life tires recovery rates. (Source: WBCSD [24])

Table 2.11 The cumulative volume of end-of-life tires collected for recovery in Italy from 2011 to 2019

Year	Recovery (kg)
2011	9,527,000
2012	41,844,617
2013	84,614,999
2014	129,965,361
2015	178,749,111
2016	228,897,665
2017	276,271,534
2018	320,520,948
2019	367,483,201

Source: EcoTyre [26]

Table 2.12 The cumulative volume of end-of-life tires collected for recovery in Italy from 2011 to 2019

Year	Recovery (million USD)
2011	323.85
2012	347.12
2013	372.87
2014	395.62
2015	411.35
2016	375.05
2017	415.28
2018	425.30
2019	434.38
2020	442.59
2021	450.03
2022	456.77
2023	462.87

Source: Brazilian Institute of Geography and Statistics [27]

According to a report by US Tire Manufacturers Association (USTMA), "Construction applications and civil engineering type applications are identified as the third-largest market for scrap tire reuse, where the tires are used as a lightweight fill or for drainage type purposes" [43]. Furthermore, as the second most widely used material in the construction engineering area, concrete consumes large amounts of waste rubber tires by replacing them with a natural aggregate of concrete. Increasing energy absorption is one of the benefits of using waste rubbers in concrete. Tire rubber particle pullout and internal tire rubber micro-cracking are two toughening mechanisms for energy consumption in the rubber-concrete matrix that cannot be observed in ordinary concrete [44]. However, as reported by Gerges et al. [45], adding rubber to the concrete has led to a reduction in strength, as shown in Fig. 2.17.

Table 2.13 Recycling and reuse of scrap tires in various industries and areas

Applications	Role	References
Building construction industries	• Concrete properties enhancement such as improvement of thermal insulation, acoustic properties	[18, 28–31]
	• Manufacturing of lightweight insulating concrete	
	• It reduces the weight of loads on the basis and time of completion and provision in the cost of transport and construction	
	• Adding rubber tires to concrete improves its mechanical and dynamic properties by absorbing more energy, better formability, and better resistance to cracking	
Rubber pavement industries	• Improve asphalt pavement performance	[32–34]
	• Rubber pavers—improved strength and reliability, both in abrasion and heavy traffic	
	• It offers less light refraction reflection rate, less traffic noise, and the reduction of maintenance costs	
Environmental remediation	• low-cost adsorbents	[35, 36]
Energy generation	• Biodiesel production	[37, 38]
	• The tire pyrolysis process produces pyrolysis oil, pyrolysis char, and pyrolysis gas	
Geotechnological engineering work	• Waste tires have been used in various geotechnical engineering applications, such as subgrade backfilling, landfill, retaining wall and slope reinforcement, etc.	[39]
Polymer processing industries	• Enhance various materials' parameters, e.g., tensile strength, toughness, or sound absorption properties	[40–42]
	• Fabrication of self-healing materials	

Farrag [46] studied the utilization of waste tire ingredients in the architectural implementation in Egypt. They found tremendous benefits in utilizing scrap tires for the construction sector by increasing the sustainability of the architectural usages and construction industry while decreasing cost and the need for natural resources and offering solutions to environmental pollution. Although rubber sound absorptive walls are costly, they are more efficient in sound absorption and reflection. On a record, highway noise contributes about 90 dBA. On the other hand, a neighborhood is considered calm at 45–55 dBA. They found sound barriers fabricated from recycled tires create a more tranquil and peaceful community. Figure 2.18 shows a compilation of materials on the absorption of sound by [47]. From the chart in Fig. 2.17, it can be seen that a granular rubber material has a suitable sound absorption property, especially toward lower frequency since the lower frequency can travel further compared to a higher frequency.

Other than that, Jedidi et al. [48] have discovered that the sound absorption and noise reduction coefficient increased with an increase in crumb rubber percentage replacement levels. They suggested that the higher sound absorption of rubberized concrete is due to increased air voids in the concrete. Holmes et al. [49] investigated rubberized concrete's sound absorbance and insulation properties at different

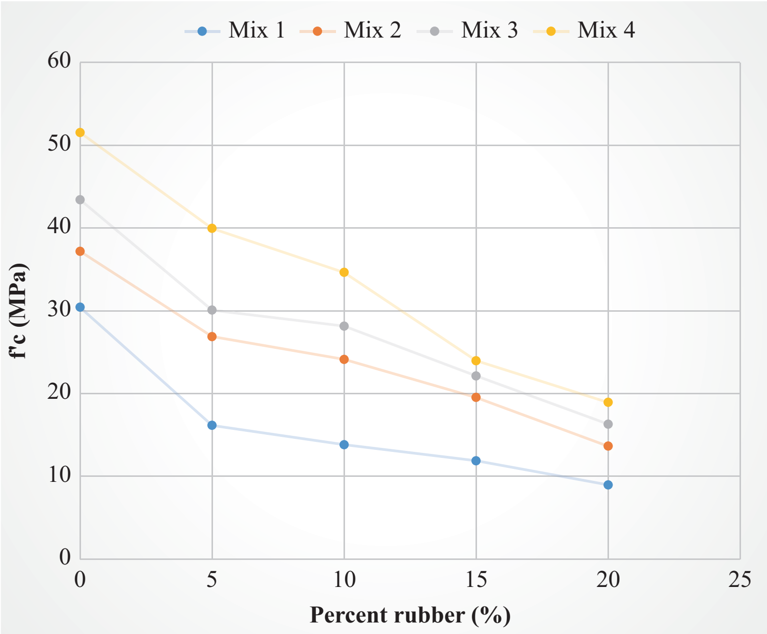


Fig. 2.17 Chart of average comprehensive strength for rubber mixture according to percentage. (Source: Gerges et al. [45])

frequencies. They found that the sound insulation performance of rubberized concrete was comparable to plain concrete for all the replacement levels. Also, they found the crumb rubber concrete was a more effective sound absorbent than bare concrete in different temperature conditions. Figure 2.19 displays a setup for testing the acoustic adsorption according to standard ISO 10534-2.

Moreover, they also notice a higher surface area of crumb rubber particles produced concrete with better high-frequency sound absorption performance. Besides, Bayraktar [18] has found the application of scrap tires in concrete and construction where they have posed several economic benefits despite a reduction of environmental pollution and prevention of the accumulation of tires consumption without the need of disposal through burning, as well as improving a lightweight insulating concrete structure. Furthermore, the manufacturing of light concrete blocks has an economic impact on the total cost of construction. It reduces the weight of loads on the basis, together with the time of completion and provision in the price of transport and construction. Additionally, it also provides high thermal insulation without the need to use coolers and heating. In Fig. 2.20, a cost comparison was made regarding the maintenance of conventional asphalt with the rubber mix. It can be observed that the costs for asphalt concrete (AC) that was mixed with rubber are significantly lower than the conventional one [51].

However, in terms of the optimum content of rubber particles, a previous study by Najim et al. [52] has recommended that the maximum rubber content should not

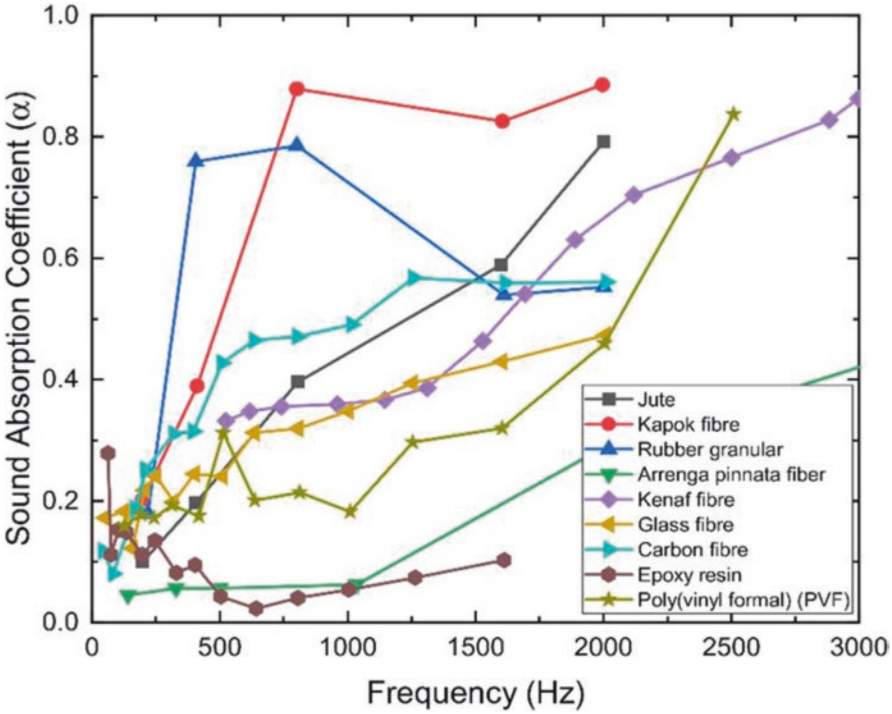


Fig. 2.18 Sound absorption coefficients of various traditional materials. (Source: Kumar and Lee [47])

exceed between 20% and 30% total aggregate volume to avoid the significant reduction loss in mechanical properties. The higher the rubber content, the greater toughness and lower strength it will be. Hence, few authors suggested studies to optimize the size, shape, grading, density, amount, and methods of pre-treatment of rubber particles on the properties of rubber concrete. Figure 2.19 shows two different techniques used in processing asphalt-rubber mixture illustrated by [53]. From Fig. 2.21, it can be seen that the dry process required extra steps compared to the wet process method in creating the material.

It was reported that the majority of ground rubber was used for asphalt rubber by utilizing approximately 220 million lb or 12 million tires annually. The most significant users of asphalt rubber in the United Stated are California and Arizona, followed by Florida, with usage anticipated to grow in other states [54].

In terms of the application of waste rubber tires for playgrounds, rubber mulch has an advantage over plant-material mulches is its elasticity, which gives it a springy quality when used in a fairly thick layer [46]. Bridgestone Corporation is developing innovative approaches to encourage the reuse of expired tires globally. They have launched Bridgestone Costa Rica's B-Happy Eco-Parks program (see Fig. 2.22) uses end-of-life tires to create playgrounds in parks and education centers. Since 2012, more than 39 playgrounds have been built in Central America and

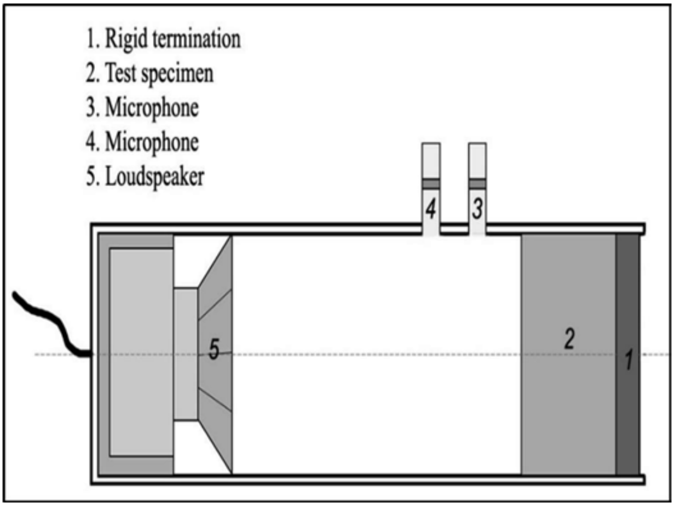


Fig. 2.19 Experiment setup for testing the acoustic absorption on the material. (Source: Modified from Standard SR EN ISO 10534-2 [50])

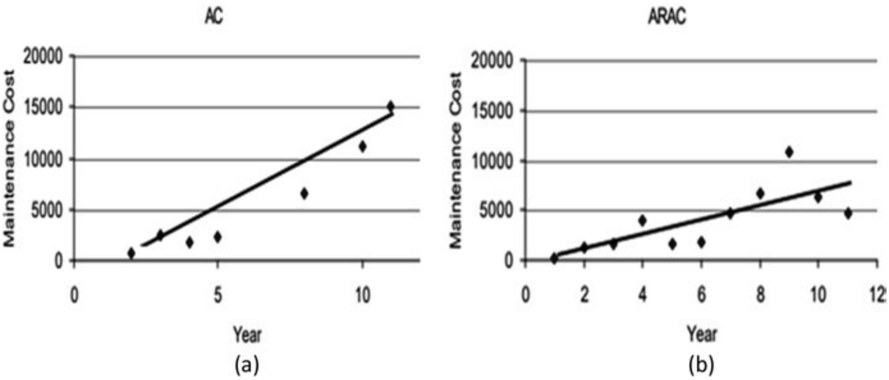


Fig. 2.20 (**a**) Maintenance costs trend for the conventional AC pavements. (**b**) Maintenance costs trend for the Asphalt-rubber AC (ARAC) pavements. (Source: Jung et al. [51])

the Caribbean under such programs [55]. Numerous countries recycle waste tires in ways other than its original intended purposes. Rather than simply burning tires or dumping them in landfills, treating waste tires as a resource and reusing them is frequently more sustainable and beneficial.

In one of the studies on, "Use of ground tire rubber in asphalt pavements: field trial and evaluation," which was conducted in Taiwan, they found the asphalt-rubber pavement test was constructed as a pilot project, demonstrating their satisfactory performance and possible potential for replacing modified asphalt in the highway road [56]. Environmental Protection Administration (EPA) of Taiwan formed a joint venture with the government engineering units that have conducted a field test plan

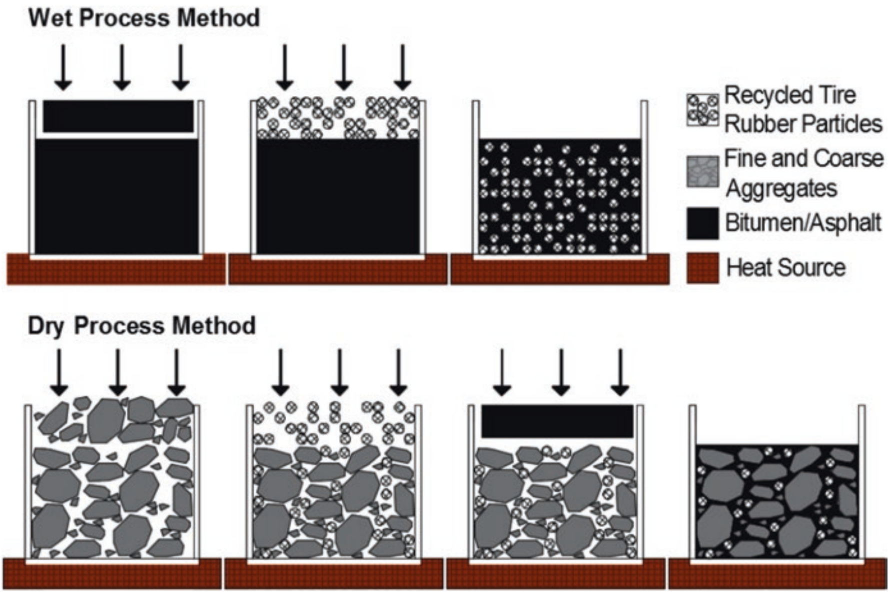


Fig. 2.21 Wet and dry process method of asphalt-rubber mixture production. (Source: Alfayez et al. [53])

Fig. 2.22 Image of Bridgestone's worker building a park using expired tires. (Source: Bridgestones Americas Inc. [55])

on road surfacing trials in 2015 to validate the performance efficiency and stability and the environmental benefits of paving roads using asphalt rubberized with a waste tire. The study showed that the use of waste tires in construction engineering works is an excellent example of the eco-friendly sustainable use of rubber resources [57].

In terms of applying waste tires for environmental remediation, Babiker et al. [58] have conducted studies on boron treatment by adsorption from water. They have investigated different pH values, initial boron concentration, adsorbent dosage, and particle size using adsorbents prepared from waste tire rubber. They found the adsorption capacity of boron by waste tire rubber is highest compared to other adsorbents reported in the literature. They've concluded that waste rubber tires are excellent and cost-effective material in removing boron from water. From Table 2.14, it was shown that a waste tire rubber has the best adsorption isotherm among the adsorbent created previously.

Another research was carried out by Wójtowicz et al. [64] on mercury adsorption using scrap tire as low-cost, sulfur-rich activated carbons. They found sulfur added to tire rubber in the process of vulcanization improved the efficiency of the adsorbent in the removal of mercury due to the high chemical affinity between mercury and sulfur. Figure 2.23 has illustrated a result of their work showing the absorption of mercury by rubber-mixed sorbent. From the chart, mercury breakthrough only occurs after 100 min of running time, which means the sorbent has fully saturated and cannot absorb any other mercury. However, the study has proved that the material can absorb mercury effectively.

On the other hand, Mousavi et al. [65] have researched waste tire rubber ash as a low-cost adsorbent to remove lead (II) ions from aqueous solution. It was found that the medium environment plays a role in determining the efficiency of the adsorbent. Several parameters such as contact time, dose injected, pH value, and temperature were tested in the study, as illustrated in Fig. 2.24.

The removal process results show that the Pb (II) ion adsorption on the waste rubber tire is an endothermic and spontaneous process. The endothermic effect due to the adsorption process increases with an increase in temperature. Besides, the removal cost is low, as the adsorbents are cheap and readily available in large

Table 2.14 Adsorption isotherms of boron for various adsorbents

Adsorbent	q_e (mg/g) at Co: 0.5 mg/L	Author	Year
Polyol-grafted MCM-41	6.11×10^{-2}	[59]	2006
Polyol-grafted SBA-15	2.61×10^{-1}	[59]	2006
Calcined alunite	1.93×10^{-2}	[60]	2009
Cerium dioxide	1.32×10^{-5}	[61]	2009
Ammine modified TG	3.43×10^{-2}	[62]	2011
Tannin Gel (TG)	2.48×10^{-2}	[62]	2011
Activated carbon (AC)	1.37×10^{-2}	[63]	2015
AC with tartaric acid	2.50×10^{-2}	[63]	2015
AC with tartaric acid	2.80×10^{-2}	[63]	2015
Activated alumina	1.17×10^{-2}	[63]	2015
Zirconium dioxide	2.78×10^{-2}	[63]	2015
Waste Tire Rubber (WTR)	1.3	[58]	2019
Chemically modified WTR	1.69	[58]	2019
Nano WTR	0.74	[58]	2019

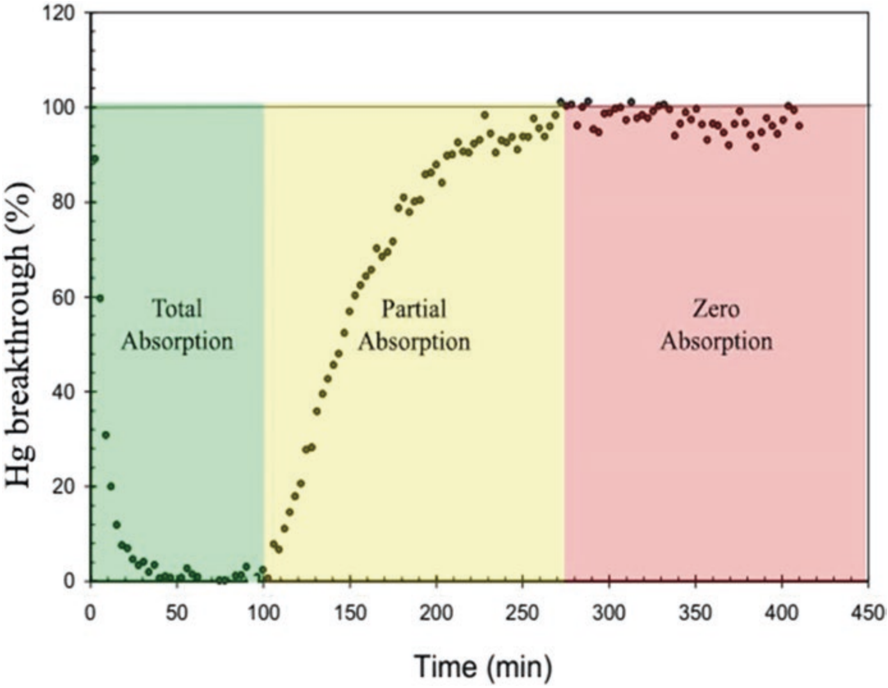


Fig. 2.23 The graph of percentage breakthrough of Hg after passed through rubber sorbent for a certain period. (Source: Wójtowicz et al. [64])

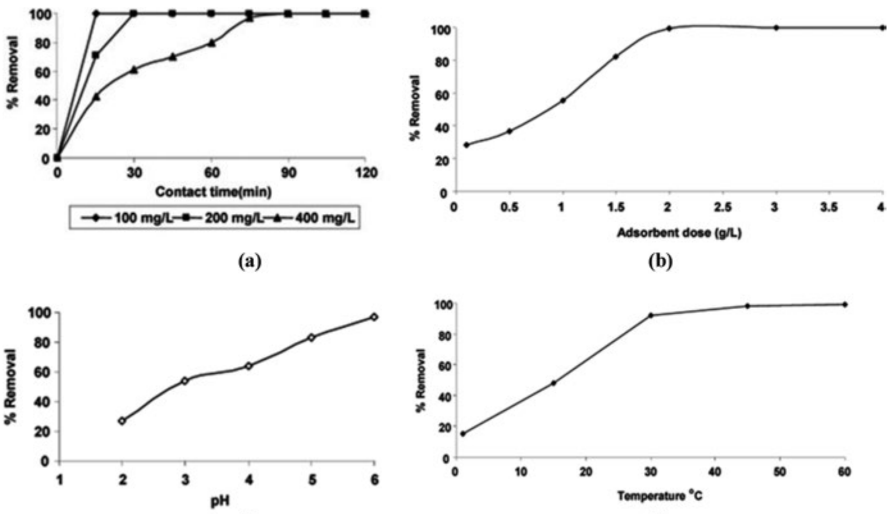


Fig. 2.24 (**a**) Effect of efficiency on contact time between adsorbent and solution. (**b**) Effect of efficiency based on doses introduced to the medium. (**c**) Effect of efficiency on pH level. (**d**) Effect of temperature toward the efficiency of adsorbent to remove Pb^{2+}. (Source: Mousavi et al. [65])

quantities. The findings indicate the waste tires would be helpful in the treatment of wastewater containing lead ions.

Derakhshan et al. [66] have conducted a feasibility study using reclaim waste tires as a suitable medium for biological growth and biofilm development in wastewater treatment systems in fixed bed sequence batch reactor. Figure 2.25 illustrates how a fixed bed sequence batch reactor was used with tire crumb [66].

The fixed bed sequence batch reactor was evaluated under different organic loading rates by assessing polyamide yam waste tires as a media. The findings found that the batch reactor's removal efficiency increased significantly by inoculating these reclaimed waste tire carriers.

In terms of waste tire application in geo-technological engineering, a waste tire is used to construct barriers on weak, compressible foundation soils. Tire shreds are suitable for this application due to their lightweight properties. Most projects have used tire shreds as lightweight fill material that is significantly cheaper than alternatives [25]. Table 2.15 shows several projects using scrap tires as subgrade fill and barriers highlighted and their locations in the United States as reported by the

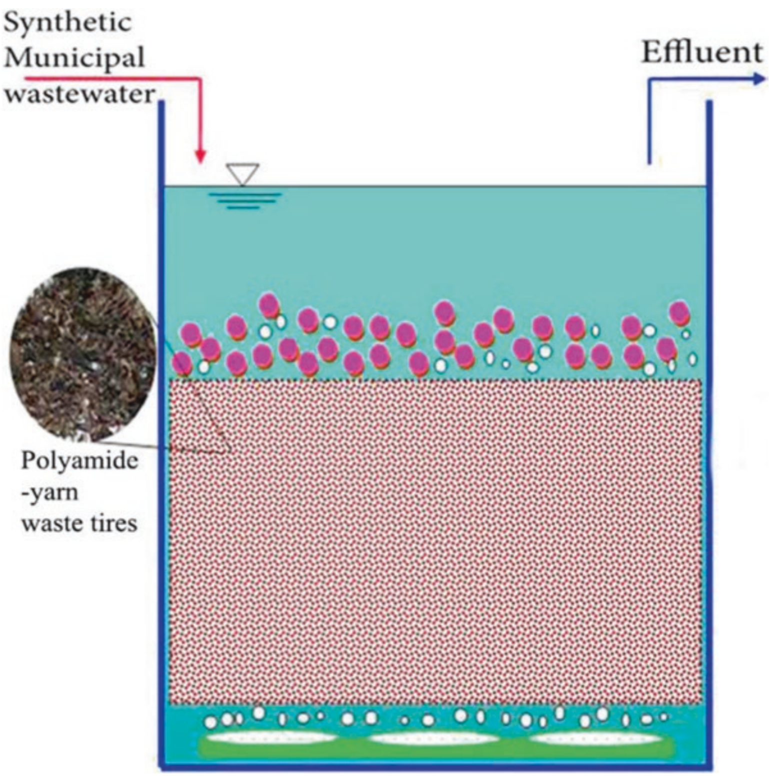


Fig. 2.25 Schematic of pilot-scale fixed bed sequence batch reactor using polyamide yarn waste tires as a medium. (Source: Derakhshan et al. [66])

Table 2.15 Several projects using scrap tires as subgrade fill and/or barriers highlighted and their locations in United States

No	Project	Location
1.	Two highway embankments on weak clay	Portland, Maine
2.	An interstate ramp across a closed landfill	Colorado
3.	Mine access roads across bogs	Minnesota
4.	Reconstruction of a highway shoulder in a slide prone area	Oregon
5.	Stabilization of a highway embankment	Topsham, Maine

Table 2.16 Project engaged in the application of scrap tires for earth retaining structure

No	Project/activities	Company
1.	ECOFLEX tire retaining wall system	SULCAL Construction Pvt. Ltd., in Australia
2.	USDA tire-faced reinforced earth retaining wall	Forest Service, Northern California
3.	ECOWALL highway noise barrier	Vienna Austria
4.	Public Works Department's earth retaining structure	Santa Barbara, California
5.	Granite aggregate filled rubber tire retaining wall	Batam, Indonesia

United States of Environmental Protection Agency (USEPA). In addition, scrap tires have also been used in various earth retaining and erosion control structures. Several projects engaged in applying scrap tires for the retaining ground system were highlighted in Table 2.16.

Hazarika et al. [67] initiated the in vitro model studies using tire chips–sand mixtures as backfill material of retaining walls to investigate the influence of sand and sand mixed with tire chips on the seismic behavior of caisson walls. They concluded from the studies that using sand mixed with tire chips prevented liquefaction-related damages. Liquefaction contributes to increment in the earth pressures against the wall; hence, prevention of liquefaction is expected to reduce the incremental dynamic earth pressures on soil structure [68]. The illustration of the test by Reddy et al. [68] was shown in Fig. 2.26.

In terms of retaining the wall, waste tires in retaining wall backfill provide adequate drainage, preventing the build-up of any excessive water pressure behind the wall's pore. Cecich et al. [69] used tire chips alone as retaining wall backfill and achieved higher safety factors against sliding and overturning compared to that using sand as backfill. Hence, waste tires also are found to improve the safety aspect of the structure.

In addition, Livingston and Ravichandran [70] presented the design retaining wall using different sand–tire chip mixtures under static and seismic conditions. They found that cost-savings of concrete per unit length can range from 23% to 44% under static loading conditions and 19–30% under dynamic loading conditions

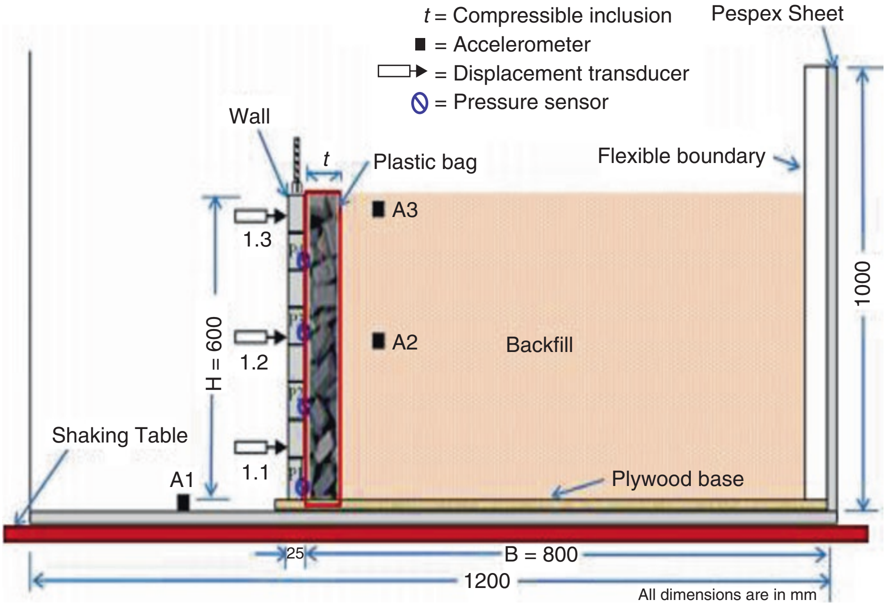


Fig. 2.26 Schematic diagram of the model wall in testing the backfill made from a mixture of sand and shred tires. (Source: Reddy et al. [68])

when using shredded rubber–sand mixture, compared to the conventional granular soil backfill. Hence, significant cost-saving also can be achieved via the application of waste tires in retaining walls [68].

As regard to energy production from waste tires, generally, there are two physical actions involved in the conversion of tires into bioenergy:

1. shredding and pyrolysis, or
2. the decomposition of the tires by exposing them at high temperatures in the presence of a particular catalyst.

The oil from the pyrolysis of tires can be used directly as a fuel, added to petroleum refinery stocks, upgraded using catalysts to a premium grade fuel, or used as a chemical feedstock. The gases from tire pyrolysis are typically composed of C1–C4 hydrocarbons and hydrogen with a high calorific value of sufficient energy content to act as fuel to provide the heat for the pyrolysis process. The solid char can be used as a solid fuel or upgraded to produce activated carbon [71]. The characteristics of the products were compared to the other products including diesel in Table 2.17.

Meanwhile, in Australia, a tire recycling process does not require the shredding of scrap tires to convert them into biofuel. The Victoria-based Green Distillation Technologies processes all kinds of tires, including the super singles with a diameter of 1.2 m. The tires are loaded into an airtight process chamber without any pre-operation, which involves shredding, crumbling, or chopping of the tires [72]. Figure 2.27 shows a general flow of process in converting a shred tire into fuel.

Table 2.17 Characteristics of the pyrolytic liquids in comparison to petroleum products

Analysis	Density (kg/m)	Viscosity (cSt)	Flash point (°C)	Pour point (°C)	HHV (MJ/kg)
Tire waste pyrolysis liquid	970	5	30	−4	42.28
Rich husk pyrolysis liquid	1050	3.609	58	ND	16.298
Co-pyrolysis liquid	832	5	75	−6.2	33.6
Diesel	827	2.61	60–80	−33 to −15	45.18

Source: Hossain et al. [71]

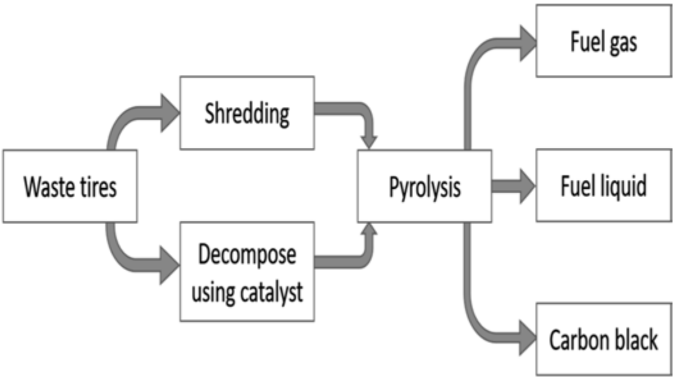


Fig. 2.27 A flowchart of processing scrap tires into fuel

Three main products were obtained from the process in the form of solid, liquid, and gas. Some of the gas produce usually cannot be derived since it has a tiny molecule. So, it was passed back to the feed burner and used directly to support the process.

Okoro et al. [73] stated that the properties of oil obtained from the pyrolysis of scrap tires were within the standard ranges for lubricant additives and could be used as a suitable lubricant additive for water-based drilling fluid. The incorporation of grounded tire rubber into polymeric matrices has proven promising in terms of the cheaper product, cleaner environment, viable processing, and non-exhaustive polymer product market [74]. Waste tires contain natural and synthetic rubbers, which are appropriate reinforcing materials for composite production—blending waste tires with virgin matrices able to save the cost of the final products and reduce the number of pure materials being applied in the process [21]. From the example earlier, where the shred tire was used as a filler for retaining walls, Reddy et al. [68] have calculated a cost-saving from this innovation, and it was displayed in Table 2.18. The average percentage saving of costs can go as high as 36% reduction.

Rubber tire waste was also applied and designed to fabricate self-healing materials to extend their life span by fully or partially repairing damage autonomously, without any external stimulus. Several healing concepts have been studied and applied to rubber matrices [75–78]. Dynamic mechanical analysis (DMA) and

Table 2.18 Comparison of costs retaining wall between conventional material and rubber-mixed

Wall height (m)	Estimated backfill material cost (INR)		% Saving	Estimated total cost (INR)		% Saving
	Sand	Mix		Sand	Mix	
3	316,316	202,362.90	36.02	498,237.60	363,634.60	27.01
6	1,350,998	927,297.10	31.36	1,866,434	1,333,351	28.56
9	3,039,746	2,104,095	30.78	4,367,339	3,050,002	30.16

Source: Reddy et al. [68]

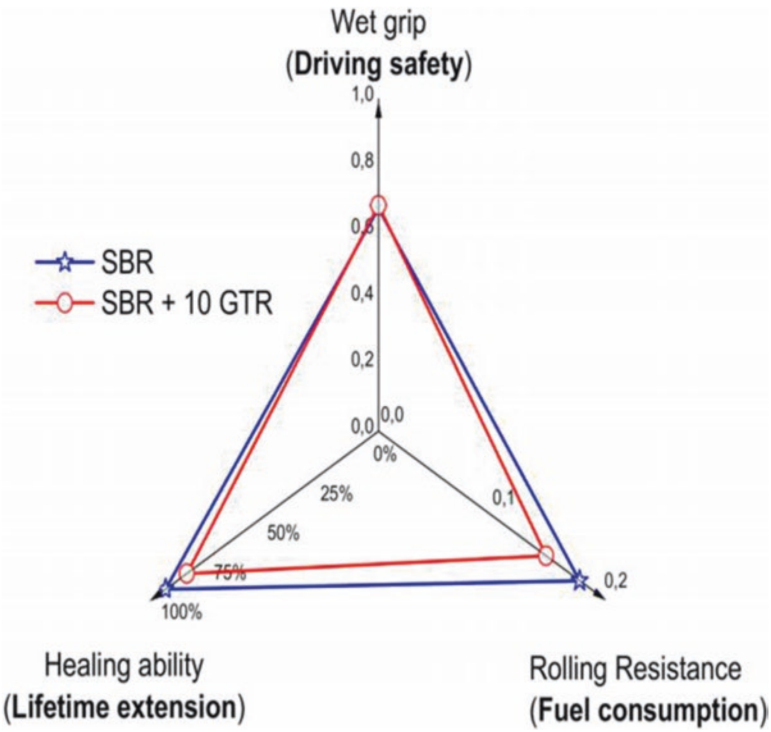


Fig. 2.28 A chart displaying a rolling resistance, wet grip, and healing ability of the SBR and GTR mixture. (Source: Araujo-Morera et al. [41])

molecular dynamics of elastomeric system using broadband dielectric spectroscopy (BDS) can be used for monitoring healing in polymers, considering that these methods are capable of performing multilevel molecular mobility analysis as a function of the structural state of the polymer [79, 80].

Araujo-Morera et al. [41] experimented using DMA and BDS on ground rubber, where they found tire compounds fully recover their stiffness and relaxation times; meanwhile, the structure of the healed rubber network becomes more heterogeneous, suggesting chain interdiffusion and the reversibility of the disulfide bonds correlated to the healing process. From Fig. 2.28, Araujo-Morera et al. [41] have showcased the performance of styrene-butadiene rubber (SBR) when added with ground tire rubber (GTR). The mixture was found to be able to reduce the fuel consumption of the vehicle while at the same time able to maintain a wet grip of the tire.

As a conclusion for the following section, many usages of scrap tires are either being studied or applied to the real world. This is considered to be quite an achievement in reducing environmental damage caused by excessive dumping. Hence, recycling not only minimizes tire waste, but the approach also helps in:

1. reducing ecological threat due to improper disposal of scrap tires
2. reducing the cost of transportation and energy for scrap tire management
3. enhancing the value to the scrap tire which is supposed to be dump in landfill by changing the waste tire to wealth
4. reducing the demand and need to produce a new source of rubber tires

2.5 Technology of Rubber Tire Recycling and Disposal

Rubber's exceptional properties make it one of the most sought-after materials in every economic sector. According to the International Rubber Study Group, total global rubber production has increased to 28.78 million metric tons since 2000, including both natural and synthetic rubber. Total global rubber consumption is expected to rise at an annual rate of 2.8% on average between 2017 and 2025 [81]. These figures, like the future problems associated with waste tires, continue to rise year after year as the number of vehicles on the road increases. As a result, an effective waste tire management system is critical for resolving waste tire issues.

Over the last few decades, landfilling has proven to be the most common method of waste disposal. The majority of rubber waste tires are disposed of in landfills. Because of the inconvenient handling and compacting of tires, most landfills will accept whole scrap tires in exchange for a hefty tipping fee. Scrap tires have climbed to the top of closed landfills in some cases, causing costly damage to the landfill cover. Scrap tires in the United States are typically cut into pieces or shredded before disposal.

Because of their convenience and simplicity, landfills have long been an important component of most waste tire management strategies. It is critical to distinguish between sanitary landfilling and open dumping. While both are essentially waste collections, landfills are systematic, monitored, and planned structures designed to reduce the environmental and public health impacts of solid waste on the local ecosystem. Although landfills do not recycle waste, they are preferable to open dumps in terms of environmental and health impacts when properly planned, constructed, and monitored.

Modern sanitary landfills are designed and constructed in a systematic manner to dispose of waste on land without endangering public health and safety. The landfill has a waterproof layer that prevents leachate from being absorbed by the soil, which could pollute the underground water further. A pipeline network is designed vertically and horizontally. These pipelines are used to remove the gas and leachate produced by waste decomposition. This type of landfill also has a leachate collection pond. Furthermore, waste is compacted and covered with dirt in sanitary landfills on a daily basis to reduce odor, fire risk, and the risk of disease transmission by insects, rats, mice, birds, and other organisms. In comparison, open dumping is a simple procedure. An open dump is a pit or location where all types of waste are brought and deposited collectively. Figure 2.29 depicts a detailed cross section of a sanitary landfill.

Monofilling is a more specialized type of landfilling in which only one type of waste is disposed of. A landfilling method separates scrap tires from other waste materials and stores them in a dedicated, licensed location, thereby eliminating mosquito breeding. When the monofill reaches capacity, it is covered in the same way that any other landfill is to reduce the risk of fire.

Incinerating tires for energy is a common waste tire management method in many countries with established waste tire management systems. While pollutant emissions from this method are a source of concern for the environment, studies have shown that when tires are used in the same application, they produce more energy and emit fewer pollutants than many fossil fuels. This resource can be used as tire-derived fuel (TDF) in a variety of facilities, including cement kilns, paper mills, and industrial boilers, as a substitute for traditional fuels such as coal. It can also be used as a coal additive with little to no effect on emissions. However, in order for energy production to be a sustainable use of waste tires, proper operating procedures must be followed. When tires are improperly incinerated, the

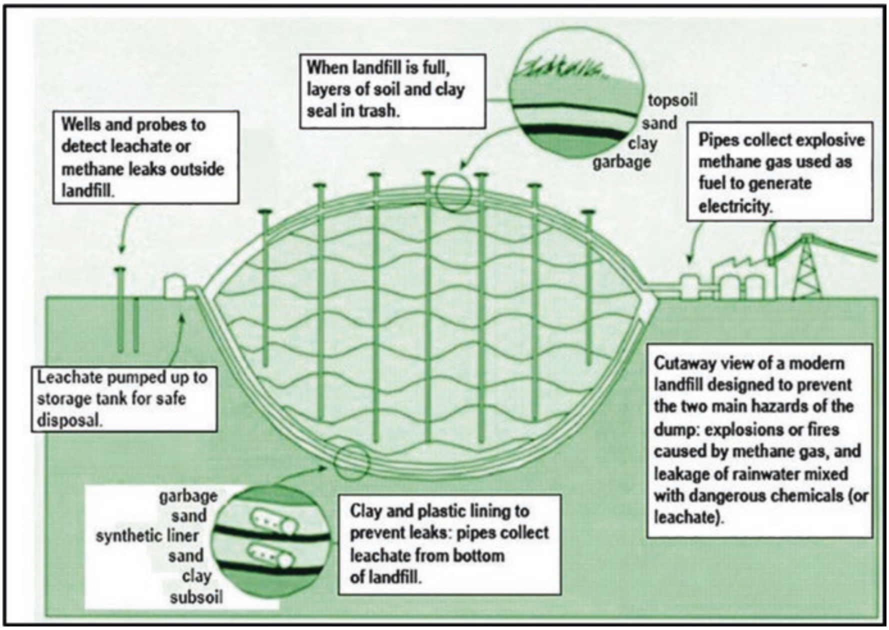


Fig. 2.29 A cross section of sanitary landfill. (Source: USEPA [82])

environmental damage can be severe, comparable to open burning. Table 2.19 compares the energy values of tire-derived fuel (TDF) to those of other fuels [83].

The lack of technical and economical disposal mechanisms makes waste tires a serious source of pollution. As waste management becomes an increasingly important global issue, some of waste products are given new life through reuse or recycling programs. The process of extracting resources or value from waste is generally referred to as recycling, meaning it is converting waste materials into new materials and objects. There are many different methods by which scrap tires are recycled: the materials may be extracted and reprocessed and redesigned, or the heat content of the waste may be converted to electricity. However, before utilizing the tires via recycling technology, it is essential to briefly understand the tires' composition. Figure 2.30 shows a cut view of the tires illustrated [84]. Each of the parts needs to be separated to obtain the purest material and increase the lifetime of the processing machinery. In general, tires are categorized into their usage, that is, passenger car tires, truck tires, and off-the-road tires (OTR).

Table 2.19 Energy values of TDF and other fuels

Fuel	Energy value
Bituminous coal	12,750 BTU/lb
Coke	13,700 BTU/lb
Natural gas	1000 BTU/cu.ft.
Oil (No. 6 fuel oil—"Bunker C")	151,000 BTU/gal
Tired-derived fuel (TDF)	15,500 BTU/lb

Source: The recycling industry: A global view [83]

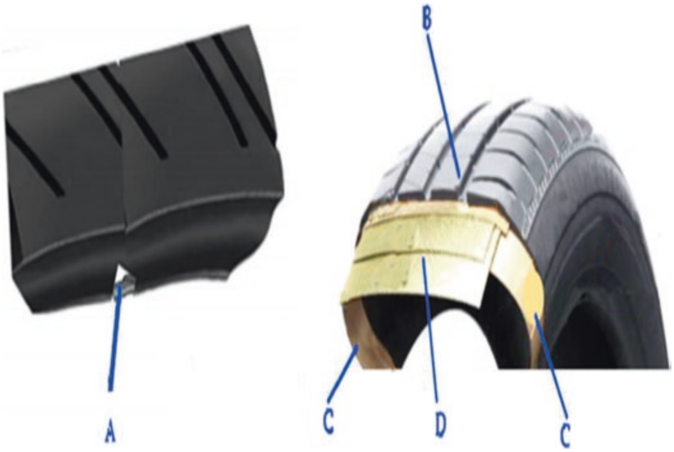


Fig. 2.30 Part of tires that needed to be separated during the scraping process. (**a**) Metal insert, (**b**) Rubber, (**c**) Rubber, and textile inserts, (**d**) Rubber, metal, and textile inserts. (Source: Dobrotă et al. [84])

The following Table 2.20 indicates the material composition of the three categories of tires:

As stated in Table 2.20, rubber is the most critical or significant component for the three different categories of tire usage. The rubber used in the tire production is previously subjected to a vulcanization process. Vulcanization is a rubber chemical process to increasing the retractile force and reducing the deformation remaining after ceasing a deforming strain by developing a three-dimensional network structure [20, 86]. Figure 2.31 shows how vulcanized rubber has strengthened the bonding of un-vulcanized rubber.

Table 2.20 Composition of tires into three class of tires

	Percentage		
Ingredients	Passenger	Truck	OTR
Rubber	47	45	47
Carbon black	21.5	22	22
Metal	16.5	25	12
Textile	5.5	–	10
Zinc oxide	1	2	2
Sulfur	1	1	1
Additives	7.5	5	6

Source: Mushunje et al. [28], Evans and Evans [85]

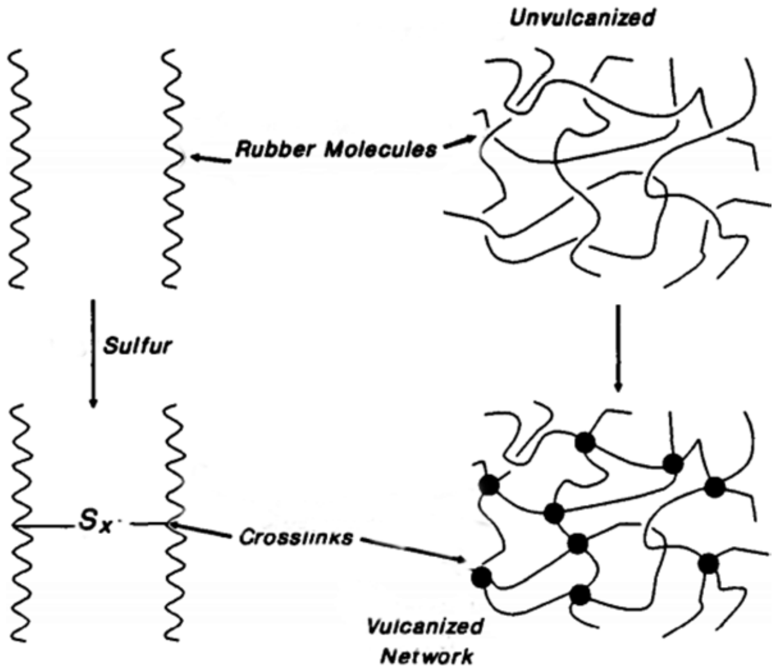


Fig. 2.31 Network formation of vulcanized rubber. (Source: The figure is modified from Coran [86])

As a consequence, vulcanized rubbers cannot be softened or remolded by heating. This particular structure of rubber makes recycling rather tricky compared with other materials such as plastics. Therefore, to recycle rubber, sulfur–carbon or sulfur–sulfur linkages between each polymer chain have to be broken under the process known as devulcanization [22]. Hence, the complexity of structure triggers the challenge of the recycling process. The selection of suitable recycling methods is essential to recycle the material efficiently in terms of processing cost, energy requirement, and environmental impact. It can be tailored to different applications and areas.

In general, there are five different phases of conventional recycling technology to recover the tire ingredients. The five phases are backing-off, shredding, grinding, electromagnetic separation of metal components, and separation of textile components [84]. Figure 2.32 shows a flow of the process in general terms.

The first phase involves cutting the selected part of the tires, consisting of the separation of heels from the rest of the tires. In this phase, all the three main types of ingredients, such as rubber, textile, and metal inserts, are isolated and found in remain tires. The second phase involves shredding of the tire waste, where shredder equipment used consists of a cylinder that grinding knives are positioned to considerably reduce the waste's size. After that, the size reduction material has undergone an electromagnetic separation to filter out any mixed metal into the tires. Finally, a series of spray systems are used for cleaning the textile waste. The systems are designed with different sizes of sieves which allow the removal of both the textile components and the rubber particles [84].

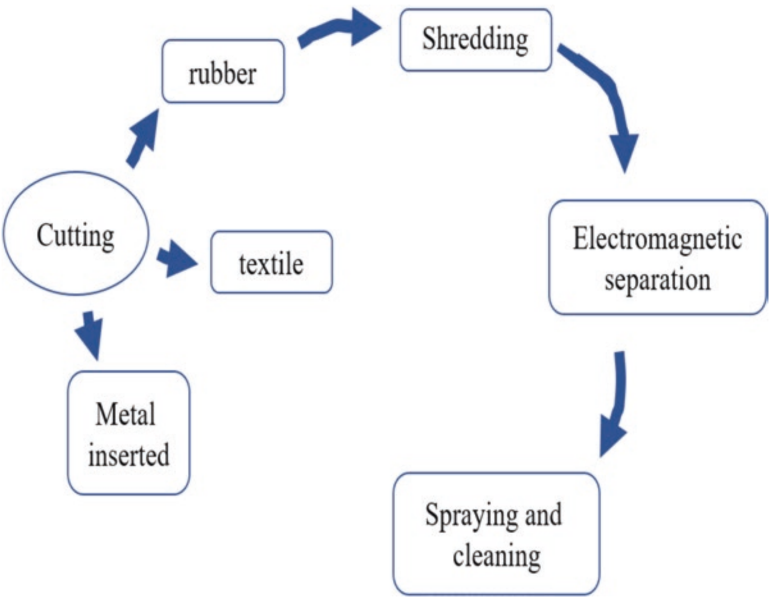


Fig. 2.32 Flowchart of separating and processing the waste tires

Table 2.21 An overview of the different rubber recycling processes [22]

Types	Description
Mechanical process	A drastic molecular weight reduction takes place due to mechanical shearing.
Thermo-mechanical processes	Employs shear stress and temperature to degrade sulfur bond selectively without affecting primary chain polymer
Microwave processes	Microwave energy is used to cleave the bonds in a rubber vulcanizate network
Ultrasonic process	Ultrasonic amplitude influences the devulcanization process
Thermo-chemical	Convert cured and uncured rubber into fuels, chemicals, and power using incineration, gasification, and pyrolysis
Chemical process	Chemical agents are used to initiate the breaking of sulfur cross-links bonds

In general, the recycling of scrap tires can be divided into two different categories (Table 2.21):

1. The scrap is separated into different sections mechanically or wholly (in crumps or shredded), and
2. chemical decomposition or separation of scrap tire contents into other materials.

Size reduction through shredding is used in mechanical processes to reduce the size of tire waste into smaller pieces. Tire waste can be reduced to a mesh with a diameter of 1 mm, and chips with a volume of 4 cm^3 are produced as feed for the pyrolysis operation. This method includes four distinct methods of grinding waste tires. Grinding is classified into four types: ambient temperature, cryogenic, wet, and high pressure water jet.

In general, mechanical grinding at ambient temperature was used to grind crumb rubber with shredders, mills, knife granulators, and rolling mills with ribbed rollers (Fig. 2.33). Crumb rubber is placed on an open two-roll mill in mechanical reclaiming processes, resulting in a drastic reduction in molecular weight due to mechanical shearing [22]. Figure 2.34 shows an illustration of a two-roll mill. The crumb rubber is ground repeatedly until the desired size is obtained. This method typically yields mulch with a particle size of less than 0.3 mm and a very rough surface. Fibers are separated from textile cords by pneumatic separators, while steel is separated by electromagnets. To avoid combustion caused by the heat generated by the oxidation of rubber grains, this procedure necessitates the use of a cooling system [89].

Wet grinding is an evolution of mechanical grinding at room temperature. The product is continuously cooled with a stream of water to mitigate the significant amount of heat generated by ambient temperature mechanical grinding. This method produces fine rubber dust with grain sizes ranging from 10 to 20 m and a high specific surface area. This dust is added to rubber mixtures for high-quality rubber products such as tires [89].

Cryogenic grinding (Fig. 2.35) utilizes liquid nitrogen as a refrigerant to cool down to a temperature less than −80 °C. The rubber is frozen into a glass-like state

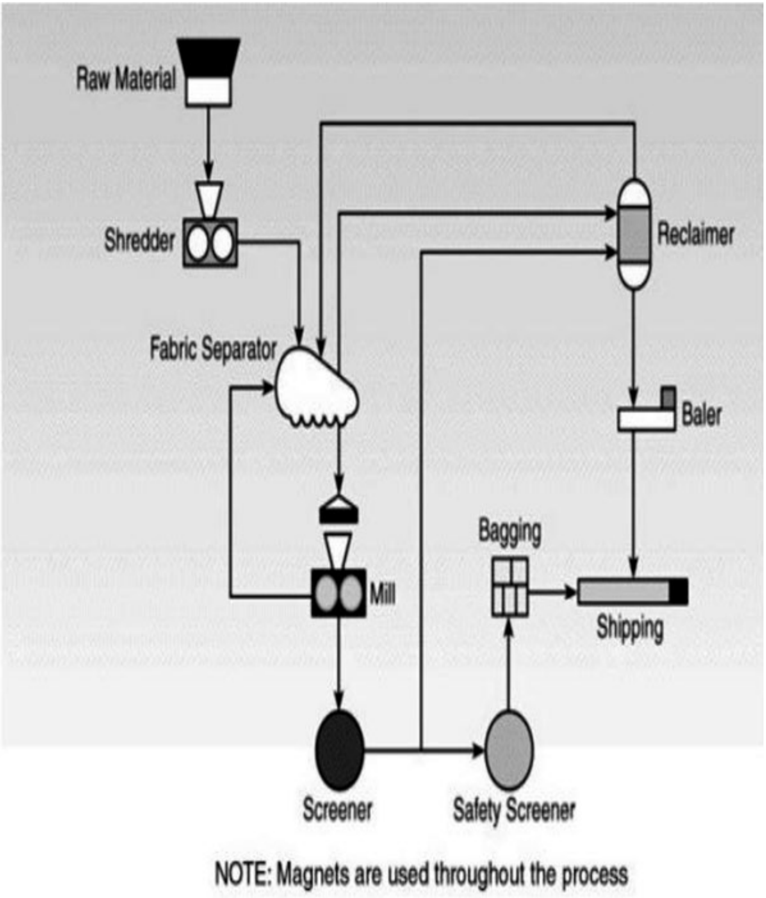
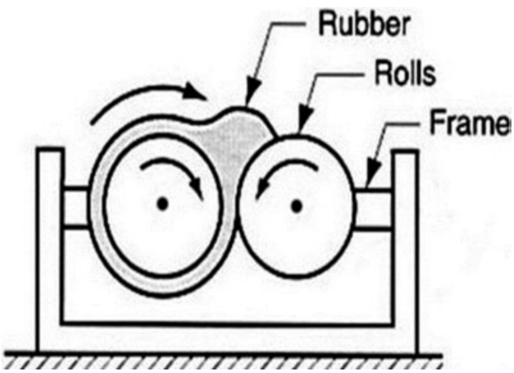


Fig. 2.33 Ambient grinding process. (Source: Recycling Made Simple [87])

Fig. 2.34 Two-roll mill for processing crumb rubber. (Source: Sapkota [88])



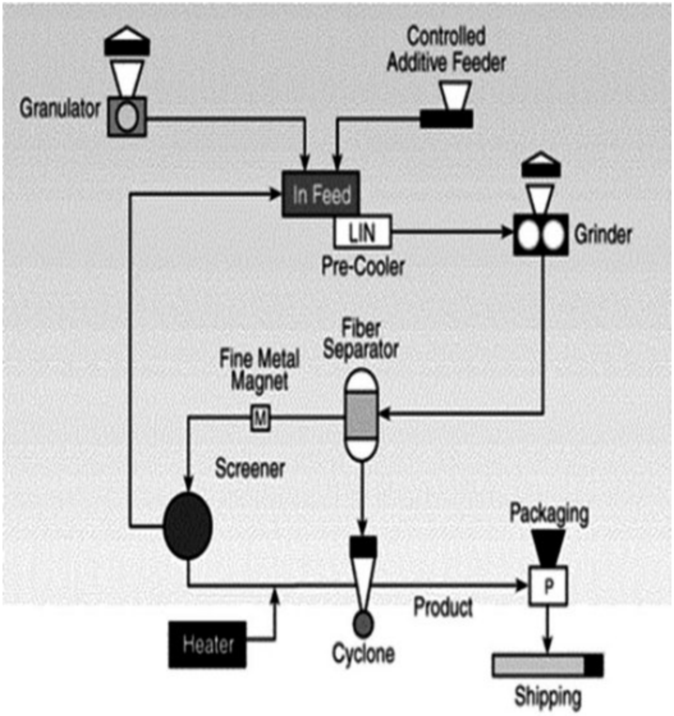


Fig. 2.35 Cryogenic grinding process. (Source: Recycling Made Simple [87])

during this process, and the tires are then broken into small particles using hammer mills. This procedure is advantageous for removing steel components and unclaimed rubber particles. Because crumb rubber obtained through the cryogenic grinding process has an angular shape, smooth surfaces, and a small surface area, it is frequently used in applications involving human contact, such as playgrounds, soil landscaping, sports surfaces, or asphalt.

Grinding large-sized tires typically necessitates the use of massive grinding machines that consume a lot of energy. The use of a water jet to grind scrap tires is a common method of recycling large-size, high-resistance tires from trucks, construction vehicles, and farm tractors. Water jet grinding requires pressures greater than 200 bar to produce high viscosity tire strips. This method has several advantages. It can be used to separate tire strips from steel cords, separate rubber crumbs from the butyl rubber membrane on the sidewall of a tire, and separate rubber material from the tread and walls. Water jet grinding yields ultra-finely ground rubber grains with a high specific surface area. Furthermore, this method is more environmentally friendly, energy efficient, and produces less pollution and noise than other grinding methods [89].

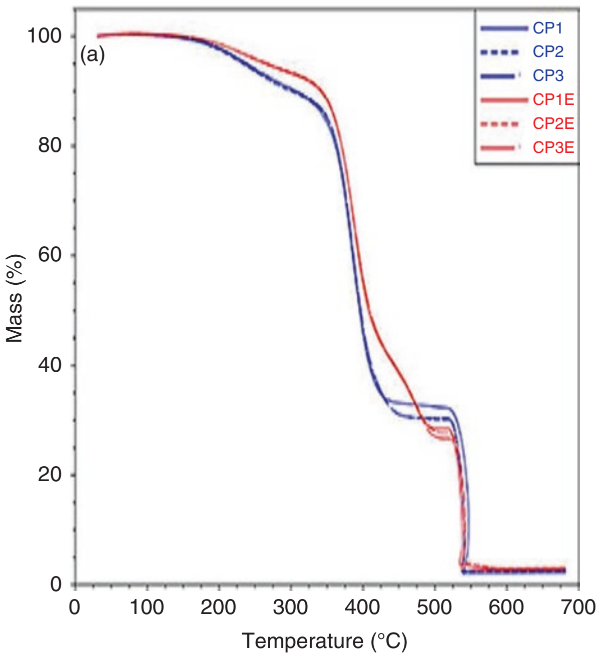


Fig. 2.36 Thermogravimetric curves of NR vulcanized before and after extrusion. (Source: Barbosa et al. [90])

While the thermo-mechanical reclaiming processes based on the application of special equipment (e.g., extruder) can result in a high degree of devulcanization, the equipment has employed a combination of shear stress and temperature to degrade the sulfur bond [90]. Furthermore, the quality of the devulcanized material was governed by the screw speed and temperature [91]. The process also can selectively break sulfur–sulfur (S–S) bonds or carbon–sulfur (C–S) bonds without interfering with the main chain of polymer [92]. From Fig. 2.36, three samples of extruded natural rubber (NR) (CP1E, CP2E, and CP3E) were undergone a thermogravimetric analysis where they were compared to the un-extruded NR (CP1, CP2, and CP3). According to the results, Barbosa et al. [90] concluded that the extruded NR has a slightly higher temperature than the un-extruded NR. In Table 2.22, weight loss (Wloss) and peak temperatures can be seen in the degradation intervals in vulcanized NR before and after the extrusion process.

In the microwave technique, electromagnetic energy is used to break S–S and C–S bonds of powder rubber. The material can absorb the energy that can increase the temperature and break the cross-link while the chemical carbon–carbon bond in the main chain is maintained [93].

Ultrasonic amplitude was found to be another effective variable influencing the devulcanization process. It can generate cavitation leading to the rupture of a

Table 2.22 Results of the thermogravimetric analysis on weight loss and degradation temperature peak

Sample	Low molecular weights	Natural rubber		EVA		Carbon black		Residue
	W_{loss} (%)	W_{loss} (%)	T_{peak} (°C)	W_{loss} (%)	T_{peak} (°C)	W_{loss} (%)	T_{peak} (°C)	W_{peak} (%)
CP1	9.6	57.3	383.9	–	–	30.1	543.6	2.1
CP1E	7.2	51.9	387.0	12.4	473.5	25.5	535.7	2.9
CP2	10.9	58.8	385.1	–	–	27.9	537.2	2.4
CP2E	6.9	53.4	386.9	12.1	479.0	23.8	539.5	2.9
CP3	8.3	61.3	385.2	–	–	27.9	537.1	2.6
CP3E	7.3	53.3	378.1	12.7	478.8	24.0	538.6	2.6

Source: Barbosa et al. [90]

three-dimensional network in the rubber matrix within a time of several seconds [94]. Due to this feature, the process can be carried out even without using chemicals.

Pyrolysis or thermochemical reclaiming of waste tires has been identified as a practical approach to reduce waste tires' huge quantities. It involves breaking down large molecular structures into smaller molecules via the means of thermal degradation. According to Rombaldo et al. [95], pyrolysis of scrap tires is one of the most environmentally friendly processes available due to the absence of greenhouse gases produced. In comparison to incineration or burning of tires, which results in the oxidation of hydrocarbons and the formation of greenhouse gases such as carbon dioxide (CO_2), carbon monoxide (CO), and silicon dioxide (SO_2), pyrolysis of tires may be a more environmentally friendly method of waste tire management.

Typically, the process generates high energy in the form of oil, gas, and char products [96, 97]. The oil produced is suitable for direct use as a fuel oil or as a raw material in petrochemical processes [95]. The low-grade carbon black produced by this process can be further processed to produce high-grade carbon black, activated carbon, or other valuable chemicals such as benzene, toluene, or xylene [98]. Temperature, pressure, heating rate, and tire particle size all have an effect on the percentage of these products. The conditions of tire pyrolysis are varied according to the amount of product desired [99]. Table 2.23 shows a summarization of final products after pyrolysis of scrap tires at different reactor temperatures.

Several industries have employed chemicals for their reclaiming rubber waste. A large number of chemical reclaiming agents for natural and synthetic rubbers have been developed. Different organic and inorganic compounds are employed to reclaim rubber. Sulfides, metal chlorides, and mercaptans compounds are generally used in those processes. Based on these chemicals, many approaches have been developed and subsequently patented. These chemical agents are used to initiate the breaking of sulfur cross-links or terminate the free radical chains formed due to C–S, S–S, and C–C bond cleavage [22, 100]. Several researchers found that the reclaimed rubber obtained from some chemical agents has a similar molecular weight with the polymer before the vulcanization process. Hence the material can be reprocessed with recovered carbon black without any separation process cleavage [100].

Table 2.23 Product distribution, elemental composition, aromaticity, and HHV for liquid obtained from pyrolysis process at different reactor temperature

Property	Reactor temperature (°C)				
	300	400	500	600	700
Solid	87.6 ± 7.8	55.9 ± 5.5	44.8 ± 0.6	44.2 ± 0.6	43.7 ± 0.4
Liquid	4.8 ± 3.9	24.8 ± 6.0	38.0 ± 1.8	38.2 ± 0.5	38.5 ± 1.2
Gas	7.6 ± 3.9	19.3 ± 2.2	17.2 ± 1.8	17.6 ± 0.8	17.8 ± 1.2
Aromatic	53.4	66.6	70.9	74	74.8
Non-aromatic	46.6	33.4	29.1	26	25.2
C (wt%)	86.5 ± 0.7	85.9 ± 0.7	85.6 ± 0.5	86.2 ± 1.0	86.0 ± 0.9
H (wt%)	10.7 ± 0.2	10.6 ± 0.3	10.1 ± 0.1	10.2 ± 0.1	10.2 ± 0.2
N (wt%)	0.30 ± 0.04	0.30 ± 0.06	0.40 ± 0.03	0.40 ± 0.03	0.40 ± 0.04
S (wt%)	1.0 ± 0.2	1.1 ± 0.2	1.4 ± 0.2	1.2 ± 0.1	1.2 ± 0.2
O + others	1.5 ± 0.8	2.1 ± 0.8	2.5 ± 0.5	2.0 ± 0.9	2.2 ± 0.9
H/C ratio	1.49	1.49	1.42	1.41	1.42
HHV (MJ/kg)	43.2 ± 0.4	42.6 ± 0.4	42.1 ± 0.3	42.2 ± 0.3	42.3 ± 0.4
Aromatic	53.4	66.6	70.9	74.0	74.8
Non-aromatic	46.6	33.4	29.1	26.0	25.2

Source: Dos Santos et al. [20]

2.6 Issues in Rubber Tire Recycling and Disposal

The accumulation of tire waste has become a major global concern. Rubber waste has a complex structure and composition, which makes it difficult to degrade. Only the natural rubber components of tires degrade naturally, which can take up to 150 years, so tire rubber will last indefinitely [101]. The synthetic components degrade solely mechanically, and naturally occurring bacteria do not consume vulcanized rubber [102].

Many environmental issues are raised by tire waste management. Pollution and sustainability are important environmental considerations. Public health and safety may be jeopardized if pollution levels are not considered when developing a management strategy. Furthermore, the strategy's ability to maintain a constant level of activity without depleting natural resources is an important consideration.

To dispose of tire waste, the majority of countries around the world have relied on landfilling. Because of its simplicity and low cost, landfilling is the most commonly used method of disposing of MSW. The primary goal of landfill site design is to include effective control measures in order to avoid negative consequences. However, due to limited space and the potential for reuse, some countries, such as the European Union, have prohibited this practice in any form since 2006 [103]. Furthermore, as the world's population has grown and tire waste has accumulated, available space for development and the construction of new landfills has become severely constrained.

The most obvious hazard associated with open dumping and accumulation of large quantities of tire pile is the possibility of explosions, which are extremely harmful to the environment. Tire fires are extremely difficult to put out. Tire waste fires generate a lot of heat, and the oily runoff that results is highly flammable and can contaminate surface water, groundwater, and soil with lead and arsenic, among other toxins [104].

Toxins are produced and released into the atmosphere when tires are burned in an uncontrolled manner. As a result, not only are firefighters tasked with extinguishing the fire at risk, but so are residents living near the landfill or tire pile. As a result, tire waste fires are frequently allowed to burn out naturally or in a more or less controlled manner until the pile is depleted.

Particulate matter emitted by improperly burned tires has been shown to settle in the lungs, putting the elderly, infants, and those suffering from asthma, heart disease, or allergies at risk [101]. Some of the chemicals reported to be emitted during fires include benzene, toluene, styrene, xylenes, M-p-Xylene, -Xylene, methylene chloride, and chloroform [101].

One of the consequences of tire waste accumulation is aesthetic concerns. Tire waste is commonly accumulated in residential buildings, commercial centers, factories, and road networks. Even if it does not cause immediate harm, it may cause frustration and incur economic costs for local residents. A tire pile also detracts from the appearance of the area or location, resulting in a decrease in property value [101]. To address the problems and health hazards associated with tire waste globally, it is critical to increase and strengthen legislation governing environmentally sustainable disposal, limit the amount of tires stored at any given site, and promote the use of tire-derived recycling products.

Despite the benefits of recycling waste tires, the application has a number of disadvantages, issues, and challenges. Figure 2.37 depicts recycling rate rates in the United States from 2013 to 2017 [105]. Rubber tire recycling has received less attention than other waste materials such as paper, glass, steel, and cans due to the final product, quality and public acceptance, financial value, marketability, and profit margin.

Table 2.24 summarizes some issues and challenges of waste tires recycling technology regarding technical, waste segregation, cost, environment, storage facilities, transportation, and administration and planning.

There are more significant challenges to successfully employing scrap tires as a fuel supplement in electric power plants in technical and processing issues. The scrap tires need to be reduced in size to fit into the fuel conveyors and mixed well [25]. This is to ensure the process can achieve complete combustion and to avoid any problem during operation. Besides, most process of recycling of scrap tires is energy-intensive due to high operational temperature. The scrap tires burn in high-temperature ovens within the temperature range of 1455–1510 °C [106]. In addition, case studies reported the status of waste tires' recycling for material and energy resources in Taiwan [57]. The authors discovered that before 2010, pyrolysis was less adopted in most recycling plants in Taiwan. This is due to the process operated at a batch mode which incurred in high processing cost. Besides, the oil fuel from

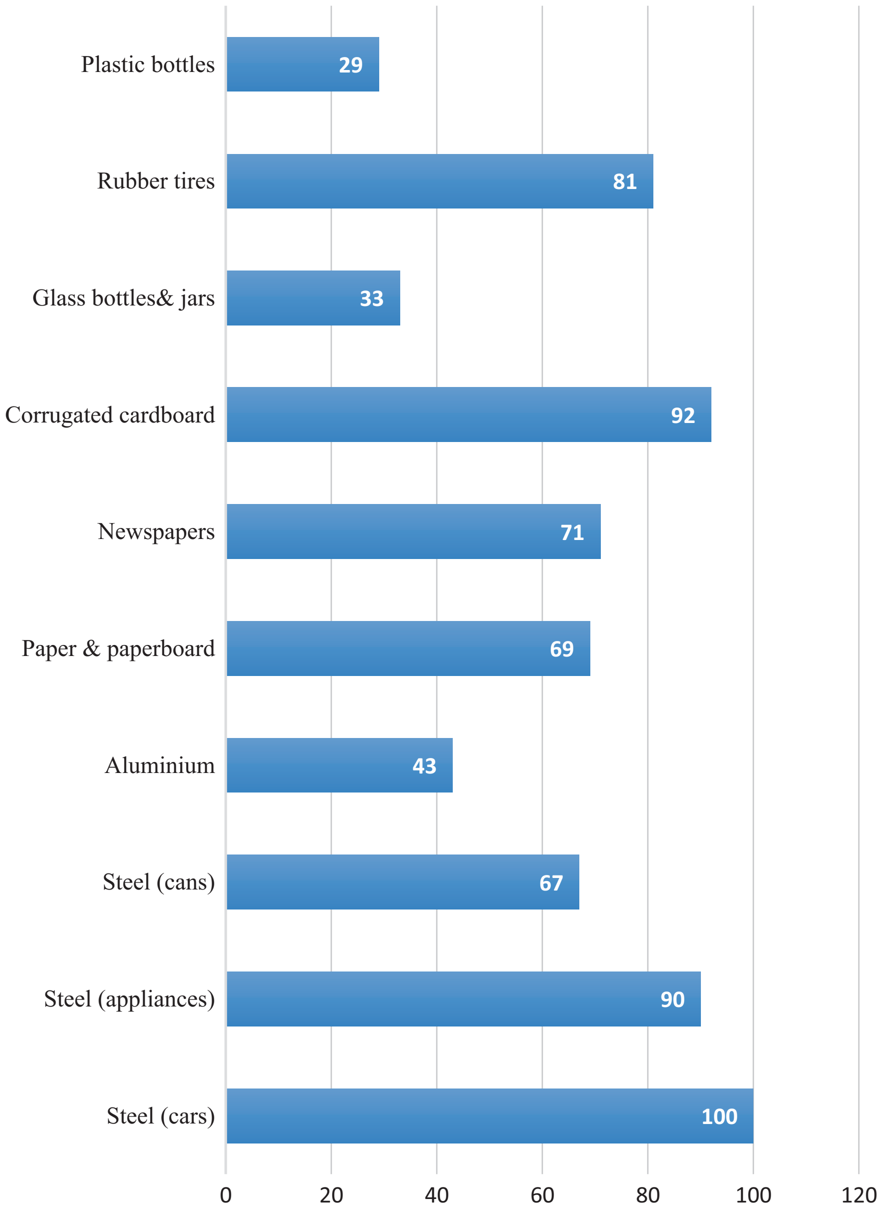


Fig. 2.37 Recycling rates in the United States for various materials (2013–2017)

tire pyrolysis can also lead to some performance problems when applied as diesel fuel in the combustion systems due to its higher sulfur, ash, and char contents.

In terms of storage facilities, large facilities and areas must stockpile the tires before the combustion process—improper stockpiling in open yards causing

Table 2.24 Summary of recycling rubber tires issues

Element of tire recycling management	Issues and challenges
Technical and processing	• High energy to properly break the material down to useful product
	• Operational difficulties
Storage facilities and environment	• Require large facilities
	• Not cover with suitable roof and platform
	• Spreading of vermin
	• Leachate from the tires may affect the solid/groundwater
Extended producer responsibility (EPR)	• A large portion of the processing rubber scrubber remaining unsold which incurred in financial cost
Sustainable resource, technology, and business	• High capital costs
	• Scrap tires resource is not locally sustainable
Local government support	• Insufficient incentive
	• Lack of recovery and recycling facilities for waste tires, lack of consistent national approach specifically dealing with the regulation of waste tires
	• No enforcement to ensure the manufactures of tires actively participated in the recycling of waste tires
Transportation	• Difficulties in transporting the scrap tires from a rural area
Safety and health issue	• Potential hazard and risk to children due to application of tire crumb in children's playgrounds
	• Risk of leakage and strong odor from the pyrolysis process causes a serious threat to the neighboring area
Public awareness	• Lack of public awareness on the importance of recycling waste tires
Administration and planning	• Lack of database system to record and track the flow of waste tires

environmental problems and becoming a breeding ground for mosquitoes and rats. The mosquitoes spread the diseases from the neighboring communities [38]. Tire piles provide a perfect habitat for insects and rodents. Water is trapped in exposed tires following rainfall. Then, this stagnant water provides breeding grounds for a variety of insects [25]. Mosquito-borne diseases such as encephalitis and dengue fever are particularly prevalent in tropical climates such as South-East Asian countries and have been reported near large waste tire piles, highlighting the importance of mosquito control [98]. If tire piles cannot be eliminated, mosquito abatement programs may be necessary to control mosquito populations within the tire piles. Figure 2.38 is an example of an unmanaged tire stockpile that can lead to severe problems for the community.

The storage should be more of a stock in transit than permanent stock. In case the store is to be permanent, Mrad and El-Samra [107] suggest indoor storage for tires is an excellent option to be applied because outdoor storage creates a breeding environment for rats, mosquitoes, and vermin. Thus, to store tires without creating a threat to human health or the environment, the storage facility needs to build based

Fig. 2.38 Image of tires stockpile dumped. (Source: USEPA [29])

on specific requirements to prevent significant risks and reduce the quantity stored per unit and place appropriate equipment. Suppose the storage facilities are not properly covered with a proper roof. In that case, floor and wall, the leachate of a toxic element from the waste tires will occur, particularly during monsoon seasons. Figure 2.39 is an image of leachate accumulation in landfill site [108].

The presence of leachate in landfills has the potential to affect the leaching of other waste products. When tire waste is deposited in a landfill cell, water content from the tire waste, rainwater, and surface water drainage all contribute to the production of leachate. The amount of leachate produced is determined by how much water percolates through the landfill cell and mixes with the waste.

More water in the waste results in more leachate, which seeps through the landfill either vertically or laterally. When an immediate impermeable cover is used on a daily basis, lateral movement occurs, and this movement may cause surface water contamination. Vertical movement will transport the leachate through the rocks and into the aquifer. The leachate, which picks up harmful chemicals or materials in waste stored in landfills, will eventually contaminate nearby groundwater. If this groundwater is used to supply drinking water, it may be hazardous to humans. As a result, all of these factors contribute to serious problems and threats to humans and the environment.

The geography and climate of a region can impede the performance of a tire waste management strategy. Higher temperatures can have a negative impact on waste tire landfills in South-East Asian countries with tropical climates. According to Wangyao et al. [109], higher methane levels in tropical regions can be attributed to rapidly degrading organic carbon in waste combined with high temperatures and

Fig. 2.39 Leachate accumulation in landfill site. (Source: Aziz and Ali [108])

moisture content. Furthermore, methane gases can accumulate in the void space of tires, rising to the landfill's surface and causing damage to the cap and structure [110]. While tires do not emit pollutants on their own, they can allow other municipal solid wastes to leach toxins by causing damage to the landfill's structure. It is difficult to prevent and even more difficult to correct the dispersion of these toxic chemicals into the surrounding environment once the landfill structure has been damaged.

Other factors regarding the facilities are the lack of local recycling facilities to create a constant supply chain of scrap tires in the market. There are no recycling industries closed to cement industries for supplying shredded tires for cement plant, which hinders the business's sustainability as importing the source from overseas is very expensive [111].

Extended producer responsibility (EPR) is an environmental program and principle adopted by certain countries that extends the responsibility of the manufacturer to fund the entire life cycle of their products, including the take-back, treatment, and disposal of the expired products. Up to this date, few countries have adopted

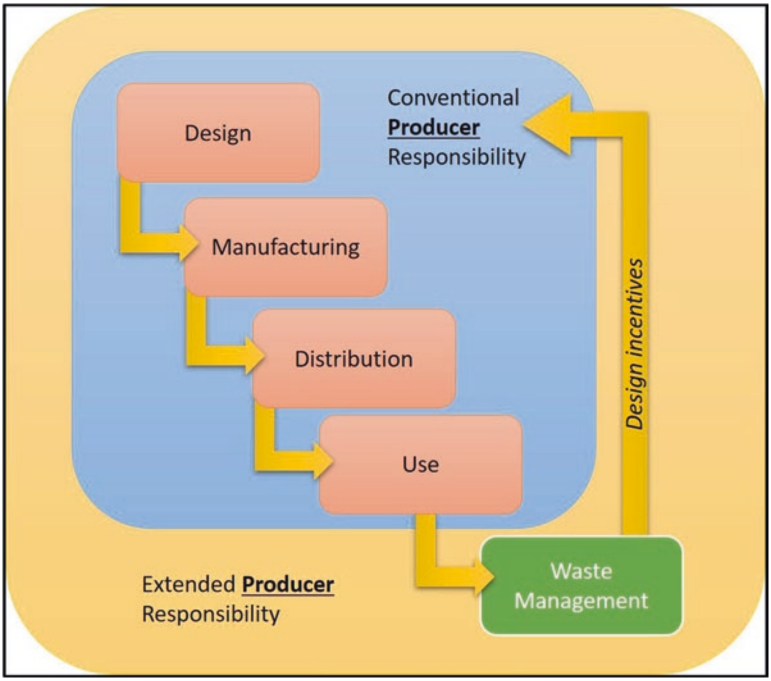


Fig. 2.40 Illustration of extended producer responsibility (EPR) program. (Source: Swachhcoin [112])

this program in managing waste tires. Through the EPR program, the units of scrap tires are converted to rubber granules increased steadily over the years. Figure 2.40 shows a flow process of EPR where the producers will take physical and financial responsibility for the proper treatment of the disposal that has reached their end-of-life limit.

However, as highlighted by a case study, the issue and challenges in this phase reported difficulties in implementing the extended producer responsibility in an emerging economy: the expired tire management in Colombia. It was estimated about 50–60% of the processed products were sold. However, the remaining significant portion of the processed products was available at storage processing facilities, which incurred financial burdens and business risks to those processing companies [113].

An audit document published by **National Environmental Licensing Authority** (Autoridad Nacional de Licencias Ambientales, ANLA) pointed out numerous issues in the tire waste collection, storage, and processing, such as environmental non-compliance (e.g., exceedance in noise level, no contingency plan, unauthorized actors), as well as reporting errors [113]. This shows that the recycling market is not yet fully established and is operated ineffectively due to a lack of the technical and managerial capacities of waste companies.

The technologies used for scrap tire recycling are not sustainable; because the equipment involves high costs and high energy consumption process and equipment [84]. The capital cost is high, and pyrolysis products do not have sufficient value to compete with commodity material [114, 115]. Besides, a report from Malaysian Local Agencies [111] has found that the unavailability of sustainable resource of scrap tires locally for the power plant contributes to the challenging factor in adapting this new alternative fuel for the power plant. The report also has included the limitation of the local market in purchasing and utilizing the secondary products, which were generated from the recycle plant of scrap tires like the steel slags, zinc, and gypsum by-products. Hence, the sustainability of business in the local market was categorized as a challenging issue. The critical point is the development of a sustainable recycling system, methods of resource recovery that will draw on this collection system to feed various alternative recycling systems and in a way that is market-driven.

Furthermore, the report also revealed a lack of a special incentive system for a power plant to generate electricity using alternative fuel. However, in Taiwan, despite the local government's support by providing subsidiaries to all the recyclers, the industry player for scrap tire recycling industry still complains that the amount of subsidy that they were received was insufficient to maintain their business operation [116]. In a case study conducted in Cyprus in 2019 concerning on management of waste tires, the authors have suggested the government reconsider the licenses that had been approved for waste tires treatment due to the total quantities available lesser than the total quantity reported to the Department of Environment [117]. In addition, a group of researchers who have conducted a case study in Tabriz, Iran, found no efficient planning by local authorities to perform recycling and establish recovering facilities to manage waste tires in Tabriz City, Iran. Hence, the authors suggested enforcing and establishing applicable legislation and policies in managing waste tires based on the experience of other countries in addressing the waste tires. They've found that the enforcement could encourage tire manufacturers to actively participate in recycling waste tires [10]. In addition, there was a case study reported in Ciudad Juárez and El Paso, the two cities located in the USA and Mexico border where the waste tire recycling program fund by the local authorities is not maintained and sustained, resulting in the waste tire management primarily left to the private sector which created a chain of burden where the cost was transferred from one level to another. Figure 2.41 illustrated a general flow of costs transferred even though the local authority provided the fund.

The consumers have to pay disposal fees to scrap tire generators; the generators have to pay to the agency that deals transporting the scrap tires. The agency has to pay the authorized end-user, and finally, the end-user charges transporters a "tipping

Fig. 2.41 Flowchart of costs transferred from the consumer before being able to submit scrap tires

fee" for accepting the scrap tires. Hence, the support from the local government in facilitating and monitoring the waste tire recycling operation is critical to ensure the business's sustainability [118].

Transportation is one of the common problems that occur in solid waste management. The challenge in transporting the waste from the source to the treatment facilities involves various factors such as distance or units to cover, the number of trips to make, different kinds of waste to carry, and type of vehicle to convey the waste, which represents additional burden in terms of costs [107, 119]. Table 2.25 shows a typical price for handling a tire from loading to unloading.

Likewise, transporting the scrap tires from the source point to the recycling facility possesses more significant challenges, especially the suitability of the type of vehicles to transfer the bulk amount of waste, number of trips, and mosty is to transport the waste tires from the remote area with low population is carrying a greater challenge [121].

Anderson et al. [122] reported in their case that the application of crumb tires in children's playgrounds poses a potential hazard to the children. They've mentioned that the US Environmental Protection Agency's (EPA) Rocky Mountain region (Region 8) Pediatric Environmental Health Specialty Unit (PEHSU) received complaints from parents who were worried when they found a small fiber found in their children's hair and clothes after the children return from playing on the playgrounds. Also, the parents can see visible haze as their children are playing in the playground. Even though there were no reported illness cases among the children due to the exposure yet, the potential hazard from the materials is still becoming a primary concern by the parents. These include the potential hazard from the material that could enter children's bodies via direct ingestion of the products or direct ingestion of surface water turnoff through the product, inhalation of dust, or direct skin contact with the material. However, a toxicology study for the hazard assessment of tire crumb for use in public playground found the only minimal hazard to children and the environment if the playground is intended to be used for outdoor activities and no solvent other than water is present on the playground [122].

In terms of safety and health, gas leakage from the recycling of tire waste plants operating using pyrolysis reactors may occur if these reactors are aging and worn out. The presence of hydrocarbon gases from the pyrolysis reactors may cause a serious strong odor. The risk of leakage and strong odor mainly occur if the plant is damaged [107].

Table 2.25 Cost of handling scrap tires

Process	Cost per tire	Cost per tons
Labor to load/unload	USD0.10	USD10
Transportation	USD0.25 to USD0.35	USD25 to USD35
Whole tire disposal	USD0.10 to USD0.30	USD10 to USD30
Profit for collector	USD0.25 to USD0.55	USD25 to USD55
Total collection cost	USD1.00	USD100

Source: Shoou-Yuh and Frank [120]

In the same reported case studies in Lebanon, the researcher found that the machine used to reduce the size of scrap tires produces loud noise, which exceeds standards set by the Environmental Protection Agency (EPA). The excessive exposure of the industrial worker to loud noise will cause damage to the hearing structure, leading to noise-induced hearing loss [123]. Based on Fig. 2.42, it can be observed that a notched sensorineural hearing loss is noted at 4 kHz, which should be relatively symmetric to other frequencies. Gunny et al. [124] have listed in their study certain factors that will lead to loss of hearing, including the level of noise, time of exposure, and individual susceptibility up to some extent.

In addition, Mrad and El-Samra [107] reported in the same case, most of the public respondents did not seem to aware of the application and utilization of recycling waste tires. However, 60% of the respondents knew the negative impact of the improper management of waste tires. In comparison, 40% of them were not aware of the harmful and negative impact of improper management of waste on the environment and human beings. Also, 83.3% of participants are willing to send the scrap tires to the tire recycling center if such facilities are available. They are also ready to ship their old tires at a specific drop-off location designed to collect waste tires. Only a minor percentage did now show interest in participating in the recycling of waste tires. In terms of costs based on the survey done by Mrad and El-Samra [107], the highest number of participants are only willing to spend around USD1 to USD20, as shown in Fig. 2.43.

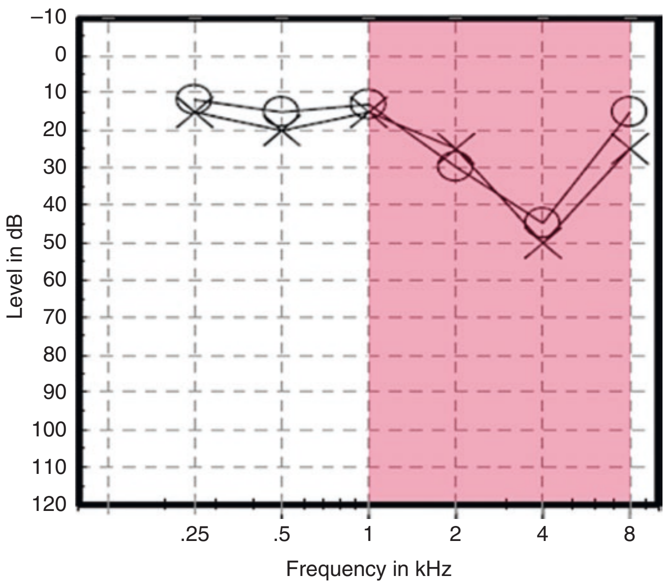


Fig. 2.42 Audiogram in noise-induced hearing loss. (Source: Gunny et al. [124])

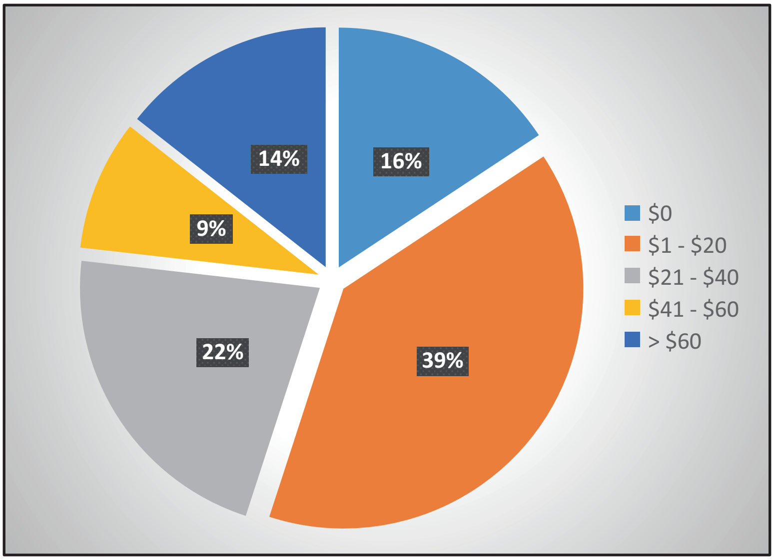


Fig. 2.43 Percentage of the respondent according to their willingness to pay for the cost of recycling. (Source; Mrad and El-Samra [107])

The survey shows that through education and awareness of recycling waste tires programs, public concern and support can be increased and strengthened. The authors also found when people received more information on the importance of proper management of waste tires. They are willing to support building such facilities financially and willing to pay an extra fee for the appropriate disposal of waste tires.

In terms of planning and administration, there are case studies conducted in Botswana, where the researchers found some issues and challenges in recycling and reuse of scrap tires. They found inefficient management of waste tires because there is no waste tires inventory record-keeping database that records the number of stockpiled waste tires in landfills and other official or unofficial dumps, or the amount stored or even abandoned. This is due to an obstacle for planning the introduction of a legislated recycling process of waste tires. Without proper waste tires inventory that records the number of stockpiled waste tires at landfills, it contributes to difficulties in developing efficient strategies for waste tire management. In addition, their finding also revealed there is no readily available data on the life span of tires, resulting in a lack of information on knowing the peak in new tire sales [125]. The lack of available data in keeping the records of waste tires dumping in landfills of such places through legal dumping or illegal dumping caused difficulties in tracking the flow of waste tires. These factors contribute to inefficient planning and management of recycling waste tires.

2.7 Conclusion

There are numerous technologies available, and some of them may provide a viable solution to the problem of tire waste disposal. Landfills have historically been the most common method of disposal and can still be found in many parts of the world. Unfortunately, many landfills are not managed properly, and the process is inefficient. In fact, a large amount of waste is disposed of in landfills, and the majority of that waste is not recycled. Recycling is one of the most effective ways for us to make a positive difference in the world we live in. The various tire recycling options demonstrated that both technical and economic options are advantageous for disposing of tire waste. When tires are recycled, we are able to dispose of tire waste in an environmentally friendly manner, which helps to maintain the balance of the ecosystem. Tire waste utilization would have a low environmental and human health impact, maximize natural resource conservation, and reduce reliance on landfill space. The proposed strategy must ensure proper management through feasible and safe collection, transportation, storage, reuse, shredding, and disposal to ensure the successful implementation of a recycling program. Local governments and the private sector must all work together to create an effective tire waste management system. Finally, in order to address global tire waste problems and health hazards, it is critical to strengthen and expand legislation governing environmentally sustainable disposal, limit the amount of tires stored at any given location, and promote the use of tire-derived recycling products.

2.8 Recommendation

The rubber tires waste disposal and recycling technology are still evolving technology and managing the rubber tires waste properly can be achieved in various ways. The following recommendations are suggested for improving of the disposal issue and recycling of rubber tires waste.

- The advanced recycling fee could be implemented to meet recycling and disposal costs.
- The quality of manufactures and imported tire should be evaluated and investigated to improve the life span of tire and hence reducing the accumulation of end-of-life tire in disposal or stockpile area.
- Improvise the extended producer responsibility program in certain countries to reduce the financial burden and risk facing by the processing company due to significant amount of unsold rubber tires granules.
- Sanitary landfill operators and related personnel must endeavor through their gained experiences to develop and to formulate the guidelines that are more concrete and applicable to reduce the associated problem related to disposal of scrap tires.
- Enforcement of policies and regulation related to end-of-life tire at different stages starting from the manufacturing/import of new tires until the end-of-life of the tire and disposal activities and recycling management.

- Encouraging policies should be implemented to promote recycling of scrap tires activities.
- Establish in situ recycling center at landfill or stockpile area to reduce the cost and issue of transportation and it would be additional income for the owner and operator of the landfill disposal area.
- Adopted strategies from successful recycling program implemented from different countries.

Glossary

Calorific Value The total energy released as heat when a substance undergoes complete combustion with oxygen under standard conditions.

Crumb Rubber Is recycled rubber produced from automotive and truck scrap tires.

Devulcanization A process that causes the selective breakup of the sulfur–sulfur (S–S) and carbon–sulfur (C–S) chemical bonds without breaking the backbone network and without degrading the material.

Extended Producer Responsibility (EPR) An environmental program and principle adopted by certain countries that extends the responsibility of the manufacturer to fund the entire life cycle of their products, including the take-back, treatment, and disposal of the expired products.

Incineration A controlled process for burning solid, liquid, and gaseous combustible wastes to gases and a residue containing non-combustible materials.

Landfilling One of the primary technologies used to dispose of solid waste.

Leachate A liquid produced from a combination of water percolation and biodegradation activities in a landfill.

Monofilling A more specialized type of landfilling that disposes of only one type of waste.

Natural Rubber Is made from the latex sap of rubber trees, especially those trees which belong to the genera Hevea and Ficus.

Open Dumping A land disposal site at which solid wastes are disposed of in a manner that does not protect the environment, are susceptible to open burning, and are exposed to the elements, vectors, and scavengers.

Pyrolysis The thermal decomposition of materials at elevated temperatures in an inert atmosphere. It involves a change of chemical composition and generates high energy in the form of oil, gas, and char products.

Recycling The process of converting waste materials into new materials and objects.

Retreading Tire The process of removing worn tread from your vehicle's tires and replacing them with new treads.

Sanitary Landfill A method of disposing waste on land without creating nuisance or hazard to public health or safety by utilizing the principle of engineering to confine the waste.

Scrap Tire Tires that have served their original purpose and have been discarded.

Synthetic Rubber Is any artificial elastomer and synthesized from petroleum by-products.

Tire-Derived-Fuel (TDF) A fuel derived from scrap tires of all kinds. This may include whole tire or tires processed into uniform, flowable pieces that satisfy the specifications of the end-user.

Vulcanization A chemical process in which the rubber is heated with sulfur, accelerator, and activator at 140–160 °C. The process involves the formation of cross-links between long rubber molecules so as to achieve improved elasticity, resilience, tensile strength, viscosity, hardness, and weather resistance.

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Chapter 3
Electronic and Electrical Equipment Waste Disposal

Puganeshwary Palaniandy, Mohd Suffian Yusoff, Lawrence K. Wang, and Mu-Hao Sung Wang

Abstract The disposal of the Wastes of Electronic and Electric Equipment (WEEE) is an emerging stream of waste that has been increasing drastically recently. The intensifying of the quantity of WEEE is due to rapid technological advancement, thus reducing the End-of-Life (EOL) and hastening the obsolescence of Electronic and Electric Equipment (EEE). The approach of handling WEEE determines the fate of contaminant substance either recycling, disposed to landfill or being incinerated, releasing toxic and hazardous chemical to environment. Nevertheless, WEEE is also known as the urban mine where it can be the source of rare earth metal (REM) and precious metal such as gold and platinum. The most important element in managing the WEEE is the enforcement of the legislation/law with initiatives from stakeholders. The option of recycling for a particular material is summarized in this book chapter. Lastly, the hazard associated with recycling is being briefly discussed at the end of a chapter.

Keywords Wastes of electronic and electric equipment (WEEE) · Electronic and electric equipment (EEE) · End-of-life (EOL) waste · Disposal · Recycle · Legislation

Nomenclature

AC	Alternating current
BER	Brominated epoxy resin
BFR	Brominated flame retardant

P. Palaniandy (✉) · M. S. Yusoff
School of Civil Engineering, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: cepuganeshwary@usm.my; suffian@usm.my

L. K. Wang · M.-H. S. Wang
Lenox Institute of Water Technology, Latham, NY, USA

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Cl_5P	Phosphorous pentachloride
CRT	Cathode ray tube
DC	Direct current
DOE	Department of Environment
DRC	Dioxin-related compounds
EEA	European Environment Agency
EEE	Electrical and electronic equipment
EoL	End of life
EPR	Extended producer responsibility
EU	European Union
EWRS	E-waste recycling site
H_2O_2	Hydrogen peroxide
LCD	Liquid crystal display
LPUR	Law for the Promotion of Effective Utilization of Resources
LRHA	Law for the Recycling of Specified Kinds of Home Appliances
MSW	Municipal solid waste
OECD	Organization of Economic Cooperation and Development
PAH	Polycyclic aromatic hydrocarbons
PBDE	Polybrominated diphenyl ether
PBDF	Poly-brominated dibenzo-*p*-dibenzofurans
PCBP	Polychlorinated biphenyl
PCB	Printed circuit board
PCDDs/Fs	Polychlorinated dibenzo-*p*-dioxins and dibenzo-furans
PCDF	Polychlorinated dibenzo-*p*-dibenzofuran
PDP	Plasma display panel
PRSWEEE	Promotion of recycling of small waste electrical and electronic equipment
RoHS	Restriction of Hazardous Substances in Electrical and Electronic Equipment
SCWO	Supercritical water oxidation
WEEE	Waste of electrical and electronic equipment
WWTP	Wastewater treatment plant

3.1 Introduction

3.1.1 Introduction

The Waste of Electrical and Electronic Equipment (WEEE), or what is known as "E-Waste," has gained significant attention in the last decades due to the increased generation of Electrical and Electronic Equipment (EEE) [1]. According to the European Union (EU), EEE has been identified as the equipment which is dependent on electromagnetic fields or electric currents in order to work properly. Such that it is used for the production, transfer, and measurement of currents and fields and designed to be utilized with a maximum voltage rating of 1000 V for alternating current (AC) and 1500 V for direct current (DC). After its end of life (EoL), this huge amount of product is disposed of because it no longer serves any purpose. One of the main contributing reasons that raise the issue of WEEE is that the current advancements in technology require the consumer to regularly change or re-new the equipment they own [2].

Different WEEE definitions are being used; however, the most widely accepted definition states that WEEE is "electrical or electronic equipment waste that includes all components, subassemblies, and consumables that are part of the EEE product at the time it is discarded." Nevertheless, there are many other definitions of WEEE given by other researchers or organization as listed by Mmereki et al. [3] (Table 3.1).

E-waste refers to any electronic or electrical equipment that has been discarded. The E-waste can include broken and/or working items that are disposed of in the garbage. Also, if the electronic/electrical item goes unsold in the store, it will often be thrown away and consider as "E-waste." WEEE has been an alarming waste stream due to the increasing production of electrical and electronic products and their potential to be a source of hazardous contaminants. E-waste is considered dangerous waste due to the toxic chemicals that naturally leach from the metals inside when it is landfilled. Moreover, inappropriate management can worsen the

Table 3.1 Different definitions of e-waste

Basel Action Network	E-waste means "discarded appliances using electricity, which include a wide range of e-products from large household devices such as refrigerators, air conditioners, cell phones, personal stereos, and consumer electronics to computers which have been discarded by their users."
Puckett and Smith	
Solving the E-waste Problem (StEP)	"E-waste refers to the reverse supply chain that collects products no longer desired by a given consumer and refurbishes for other consumers, recycles, or otherwise processes wastes."
European Union Waste Electronic and Electrical Equipment (EU WEEE) Directive	Waste from electrical or electronic equipment refers to "all components, subassemblies, and consumables, which are part of the product at the time of discarding." In the Directive 75/442/EEC, Article 1(a), waste is primarily defined as "any substance or object that the holder disposes of or is required to dispose of pursuant to the provisions of the national law in force."
SINHA	E-waste can be described as "an electrically powered appliance that no longer satisfies the current owner for its original purpose."
Organization of Economic Cooperation and Development (OECD)	E-waste can be classified as "any appliance using an electric power supply that has reached its end of life."
[4]	Electronic or electrical equipment that was or is expected to be scrapped, including all parts, subassembly, and consumables that belong to the product at the time of disposal
[5]	Old or EOL or discarded electricity equipment or, more broadly, outdated electrical and electromagnetic field-dependent appliances are working correctly.

global warming effect. Therefore, effective WEEE management can help to mitigate the release of hazardous and toxic contaminants to the environment, such as heavy metals, micro-plastics, and others. For instance, the improper disposal of CRT to landfills causes the leaching of lead, leading to groundwater contamination [6].

3.1.2 Current Situation

In 2019, the proportion of documented collection and recycling of E-waste was only 17.4% (9.3 million tons) from the total of 53.6 million tons, while the other portion is not properly documented; thus, the fate of unrecorded WEEE remains unknown. Meanwhile, the amount of generated WEEE is projected to increase to 74.7 million tons in the year 2030 [7]. The ability to assess accurate information in the generation, recycling, and collection of WEEE has been a major challenge in the global effort in handling this waste [8]. Details on WEEE production can differ by region and/or country due to different reasons, including the different variations in waste definitions and classifications between these regions/countries, technical equipment used, consumer usage habits, and differences in lifestyle standards around the world. Therefore, the performed comparison that has been done might not provide an actual performance of the waste governance [3]. This alarming and threatening situation has enforced the stakeholders to take drastic steps in order to control the adverse effects at the minimum level.

A concept of waste hierarchy was introduced in 1990, which listed different options for the treatment of WEEE (Fig. 3.1). In this hierarchy, the best-selected option considers preventing waste in the first place. This option, however, is extremely challenging due to the rapid advancements in technology. The revolution of technology plays a major part in the increment of WEEE. For example, a digital switchover for TV, which requires replacing the conventional analog terrestrial transmission with solely digital signals, has impacted the quantity of WEEE in the area of Hampshire, UK [2]. Nevertheless, the second approach included in the hierarchy proposes to cut down the amount of generated E-waste. This E-waste mitigation approach involves effort in the reduction of a waste bulk quantity as well as the hazardous substance included in the EEE product. The reduction of a hazardous substance on the other hand requires an initiative from stakeholders in establishing a useful policy or upgrading the existing legislations. The European Commission's Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS) directive suggests that the only way to guarantee that dangerous substances in goods are reduced is to replace them with less lethal materials. This would curb the use of these toxic substances, leading to increased recycling's possibilities and profitability, as it minimizes the risk of exposure to hazardous substances to manpower during the recycling processes [9].

On the other hand, the disposal of WEEE in landfills was selected as the worst option for the management of E-waste. A study by Ferronato and Torretta [11] has

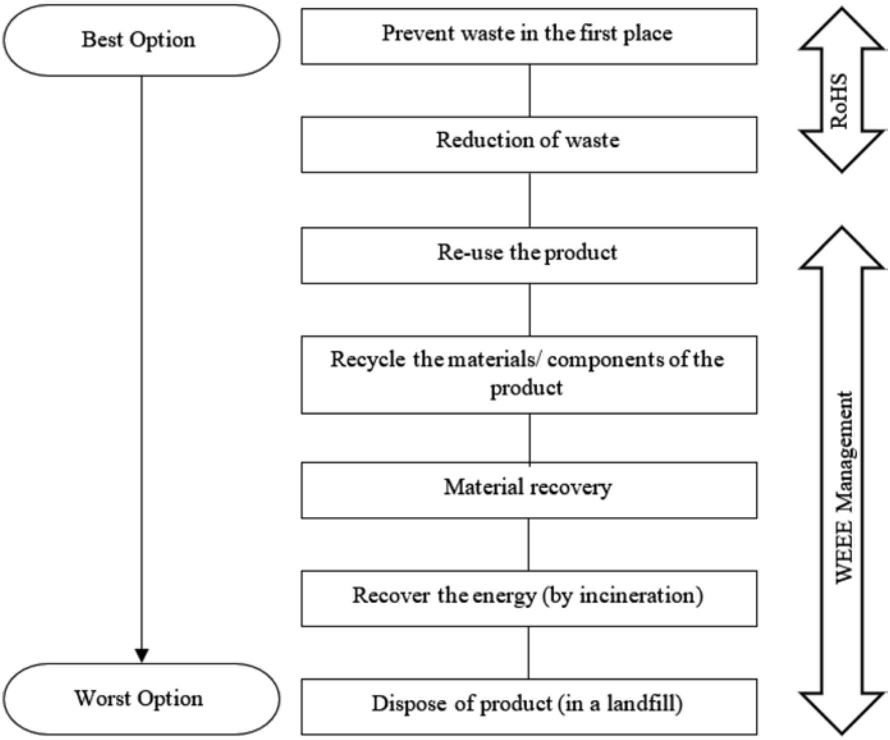

Fig. 3.1 The waste treatment hierarchy [9, 10]

summarized the effect of WEEE disposal in a landfill on the environment, including an elevated heavy metal concentration in soil and groundwater, whereas Olafisoye et al. [12] have concluded that heavy metals concentrations in water abstracted from the well is higher as the location of the well is closer to the disposal area.

Despite a negative perspective of WEEE, it offers a colossal opportunity for resource mine via material recycling. The term "urban mining" specifically defines the resource extraction from WEEE. The raw materials that have gained attraction include precious metal and rare earth metal [13]. In addition, recycling the material aids in obviating the necessity of the production of virgin materials [14].

3.1.2.1 Contributing Factors/Issues in WEEE Management

There are several factors that can complicate E-waste management in developing and transition countries. These factors can include (1) unlicensed and illegal trading E-waste recycling, (2) insufficient organizational structure, (3) absence of financial, technological, infrastructure and technically skilled human resources, (4) insufficient description of the stakeholders' roles and responsibilities, and the organizations involved, and (5) inactive community engagement in e-waste management [3, 15]. The most important factor in standardizing waste direction is policy/legislation/regulation. The lack of strict legislation would make law enforcement ineffective. Depending on current events, such policies or laws require to be revised frequently. For example, [8] has indicated that there is a certain weakness in the authorities of Japan regarding the banning of WEEE trading that need to be amended. The legislation that works in the origin region might not produce a similar result in another region. Thus, the design of such legislation should be outlined to suit local authorities and the capability of facilities.

Device stockpiling is a convenient, simple choice for the fairly well-informed customer who may hesitate to throw electronics in municipal waste but who may not be adequately informed or willing to recycle the object and who may also be concerned about data protection. The occurrence of device stockpiling is increasing rapidly [2]. It has been reported that there are approximately two mobile handsets in circulation for every person in the population that are not in use in Norway [14]. Jayaraman et al. [16] found two important pieces of knowledge in an individual that related to proper disposal of laptop. The awareness of how to properly dispose of a laptop and laptop literacy has positively impacted an individual decision in laptop disposal.

The accelerated technology progression has brought more conveniences in human life. The EEE product has become smaller in size, better in overall performance, cheaper in price and become more user-friendly. All these attributes promote the increment of the usage and obsolesce of EEE products which also directly influence the rate of WEEE generation [16]. The relevance of the cathode ray tube (CRT) as an example has become obsolescence in the presence of a better choice, such as the Liquid Crystal Displays (LCDs) and Plasma Display Panel (PDPs). The transition of this technology brought a large quantity of CRT disposal in 2015 in Europe, and the situation worsened when the demand for leaded glass that is one of the materials needed to produce CRT, has depleted [17]. Technology advancement has made connectivity between equipment via network possible. It is expected that more daily-life items will be IoT-enabled from refrigerators, air conditioned and even coffee mug, which will increase the quantity of EEE personal items and some of these items are easily damaged. This trend is directly increasing the production of WEEE as some of the IoT items are not sharing-based items. Short life cycles and fewer repair options for EEE also contribute to WEEE quantity rise.

Informal recycling not only contributes to inaccuracies in inventory assessment data that local governments need to recognize WEEE production, but it can also have some negative effects on the environment and the economy. By-products such as heavy metals, dioxins, and furans are generated by informal E-waste disposal practices (e.g., open burning, incineration, acid metal stripping, and acid baths) [15]. Furthermore, it raises the risk of labor being exposed to toxic substances as a result of improper facilities and insufficient personal protective equipment [18]. Small WEEE (sWEEE) has always been disposed of as normal municipal solid waste (MSW) due to its size. Portion or components of WEEE are also often mixed with MSW and disposed of in open dumpsites [11].

3.1.3 Classifications on WEEE

The first step in managing WEEE is to categorize the waste based on their character (material, size, etc.). Table 3.1 shows the earliest categories established by The Council of the European Union in 2002. This category is created based on multiple factors such as original functions, sizes, weight, and material composition. Other than that, each category has a distinctive character in terms of waste quantity, economic value, a risk to human health, and recycling technology [19]. Most studies are still referring to the earlier categories as the enforcement of new categories started in 2018. Based on the first categories established by the EU, more than 93% of the weight of WEEE generated comes from items 1 to 4 (Table 3.2). Table 3.3 indicates the classification of WEEE in India [21].

3.1.4 Waste Characteristic

Babu et al. [1] have divided the WEEE material into six major groups, including ferrous metal, non-ferrous metal, plastic, glasses, wood, and others. However, based on the latest categorization, the materials divided into only five groups, which include ferrous metals, non-ferrous metals, glass, plastics, and other materials [13]. This is solely due to the fact that less wood has been used in manufacturing EEE items, while plastic has taken more place in the production of EEE. The composition of different group diverse widely depends on the items. Table 3.4 summarizes various items and their composition. The large household appliance contains 61% of ferrous metal, whereas small household appliance contains lesser amount of

Table 3.2 WEEE categories [20]

Categories of EEE according to the WEEE Directive (2002/96/EC)	Categories of EEE according to the Recast WEEE Directive (2012/19/EU), to apply from 15 August 2018
1. Electronic and consumer equipment	1. Equipment for temperature change
2. Medical devices	2. Windows, displays, and screen equipment with more than 100 cm^2 of surface area
3. Toys, leisure and sport equipment	3. Lamps
4. Automatic dispenser lighting equipment	4. Large equipment (any external dimension more than 50 cm)
5. Large household appliance	5. Small appliances (no external dimension more than 50 cm)
6. Small household appliances	1.1.1.6. Small telecommunications and IT devices (no more than 50 cm external dimension)
7. IT and Telecommunications equipment	
8. Electrical and electronic tools	
9. Monitoring and control instruments	

Table 3.3 Classification of WEEE in India [21]

Type	WEEE
IT and communication equipment	Printers, monitors, CPUs, typewriters, mobile phones, keyboards, chargers, compact discs, headphones, batteries, remotes, semiconductors, etc.
Households	Air conditioners (AC), laundry machine, LCD/Plasma TVs, refrigerators, microwave oven, mixture grinder, etc.
Consumer electronics	Video games, remote control cars, DVDs and players, iPods, etc.

Table 3.4 Material concentration in WEEE [22]

Items	Ferrous metal	Non-ferrous metal	Glass	Plastic	Other
Small household appliance	19	1	0	48	32
TV, radio, etc.	11	2	35	31	22
Telecom	13	7	35	31	22
Large household appliance	61	7	3	9	21
IT equipment	43	0	4	30	20

ferrous metal 19% and 48% plastic. The composition of plastic also is the highest in telecommunication equipment which consist of 30% from total weight [23].

3.1.4.1 Plastic

The usage of plastic or polymer in the manufacture of EEE items has increased rapidly due to several reasons, such as its durability, lightweight, prevention of corrosion, etc. The advantages of this material lead to the rise of the WEEE plastics amount, and its improper disposal causes adverse effects to the human and environment. Hence, from an urban, occupational, and economic standpoint, managing the disposal or recovery of plastics is critical; WEEP includes harmful compounds that may result in chemical pollution if improperly recycled or disposed of or high production costs if properly handled. The ability to find uses for recycled plastics is primarily determined by the type of polymer, the cost of recovered material relative to virgin material, and the amount of work necessary to recover material of the required purity and quality [23]. The recycling of plastic can reduce the need for raw materials, and 80–90% energy savings can be achieved by using recycled plastic compared to virgin materials [24]. A common practice for plastic and metal part separation can be accomplished by a mechanical/gravitational process [25]. However, different types of plastic must be separated prior to remolding due to their difference in characteristics; thus, a systematic system is needed to eliminate unwanted issues in the recycling process [24]. The type of polymer and its use are listed in Table 3.5.

Plastic WEEE does not only consist of polymer material but it is also reported some heavy metal concentrations. For example, a plastic housing of monitors from sets of personal computers contains As, Cr, Fe, Cu, Al, Ni, Sn, Zn, and Pb in a study

Table 3.5 Typical applications of plastic polymers in EEE [22]

Materials	Applications
PS (HIPS)	Components inside refrigerators, housings of small household appliances, data processing, consumer electronics.
PC/ABS	Housings of ICT equipment and certain small household appliances (e.g., shavers, kettles).
PP	Components inside castings of small household appliances (coffee makers, irons, etc.), laundry machines, and dishwashers.
	Internal electronic components.
ABS	Housings and casting of phones, small household appliances, microwave ovens, flat screens, and certain monitors.
PPO (blend HIPS/PPE)	Housings of consumer electronics (TVs) and computer monitors and some small household appliances (e.g., hairdryers)
	Component's printers and copiers
PC	Housings of ICT equipment and household appliances.
	Lighting.
Epoxy resins	Printed circuit boards (PCBs).

by [26]. In 2017, 3,488,000 tons of WEEE were collected in Europe, with 732,000 tons corresponding to the WEEP group. The main contributors to this number are large, small, and small IT/telecommunication equipment, which accounts for two-thirds of the total WEEP collected. Table 3.6 shows the composition of the plastic materials in different categories. It can be observed that large equipment consists of 17.53% of plastic component, while the temperature exchange equipment has the least amount of plastic use 1.43% used as part of the equipment. Plastic has become more prevalent in EEE due to its moldable nature and oxidation resistance compared to metal.

3.1.4.2 Metals

WEEE contains more portion of metals compared to other materials. Metals in WEEE can be divided into two major groups, which are ferrous metal and non-ferrous metal. Ferrous metals can also be divided into precious metal and rare earth metal [20]. Approximately 60% of the weight of WEEE is composed of metal, while 15.21% is plastic, and 11.87% is LCD/CRT screen [28]. The recycling of metal sources from WEEE possesses significant merits over the processing of primary metals. For example, it utilizes less energy and produces less secondary by products [28].

Table 3.7 summarizes the heavy metals, their application and their recyclability. Elements such as, As, Br, Cd, Cr, Hg, and Pb are extremely toxic, and they have been associated with causing damages to the central and peripheral nervous systems. They can also lead to heart, lungs, liver, kidneys, brain, hearing, and cognitive development. Furthermore, such heavy metals (As, Cr, Cd, Eu, Rh, Ni, etc.) are considered carcinogens and can cause other adverse health effects on humans.

Table 3.6 Percentage composition of WEEE plastic for different categories [27]

	ABS	PA	PC	PBT	PC + ABS	PE	PMMA	PP	PS	PUR	PVC	SAN	Others
Screen and monitors	21.89	–	2.66	2.71	8.18	0.02	1.57	12.19	40.62	–	0.01	10.14	10.14
Lamp	7.55	12.13	13.23	23.47	–	0.72	6.38	3.43	11.15	–	7.13	14.80	14.80
Temperature exchange equipment	2.71	0.23	0.12	–	–	0.41	–	11.63	42.27	37.2	3.88	0.12	1.43
Small equipment, small IT and telecommunication equipment	35.62	0.48	4.17	2.35	7.49	1	1.13	14.55	15.91	0.04	0.35	16.72	16.72
Large equipment	16.67	0.21	0.95	0.98	1.56	0.92	0.39	56.4	2.81	0.36	3.18	17.53	17.53
Total	24.65	0.36	2.72	1.8	5.14	0.79	0.86	23.68	19.13	5.17	1.47	14.10	14.10

Table 3.7 Hazardous substances in WEEEs and its recyclability [29]

Substance	Use in EEE	Recyclability
Cd	Rechargeable batteries, blue-green phosphor emitter/housing, chip resistors, and semiconductors	0
Au	Connectivity, conductivity, PWB, connectors	99
Ti	Pigment, alloying agent/housing	46
Al	Structural, conductivity/housing, CRT, PWB, connectors	80
Li	Rechargeable batteries	0
Se	Rectifiers/PWB	70
Pt	Thick-film conductor/PWB	95
Mg	Structural, magnetivity (steel), housing	0
Sb	Diodes/housing, PWB, CRTs, printed circuit boards	0
Cu	Conductivity/CRT, PWB, connectors	90
Ni	Structural, magnetivity (steel), housing, CRT, PWB	80
Hg	Batteries, switches/housing, PWB	0
As	Doping agents in transistors/PWB, light-emitting diodes	0
Cr	Decorative, hardener/(steel) housing	0
Pb	Metal joining, radiation shield, CRT, PWB	5
Rh	Thick-film conductor/PWB	50
Ag	Conductivity/PWB, connectors	98

3.2 Effect to Environment

3.2.1 General

Recycling is carried out in low-income countries under uncontrolled conditions, resulting in severe contamination of the environment. In countries with informal recycling areas, elevated concentration levels of organic and metallic pollutants have been detected in the soil, air, sediments, and water. The administration of these pollutants into the environmental compartments poses a potential health hazard to the environment, which has long been recognized but has yet to be quantified. Generally, WEEE is affecting the environment in two ways (Fig. 3.2). The first one can be described as the direct pollution from the WEEE processes and the second one is the indirect effect on the environment [30]. The latter can also be categorized as the by-product of the recycling process. Original materials, electronic and electrical equipment components; auxiliary materials used in the recycling techniques; and by-products produced from primary components change are the three major classes of substances emitted through recycling [30].

Contaminants emitted into the atmosphere as a result of informal WEEE practices can end up in the homes or workplaces of those who live or work nearby. In fact, exposure refers to the contact of humans with contaminants. Inhalation of polluted air; absorption of polluted water, soil, or food; and dermal contact with a polluted intermediate, such as water or soil, are examples of common exposure mechanisms for environmental pollutants [31]. Based on Fig. 3.3, the

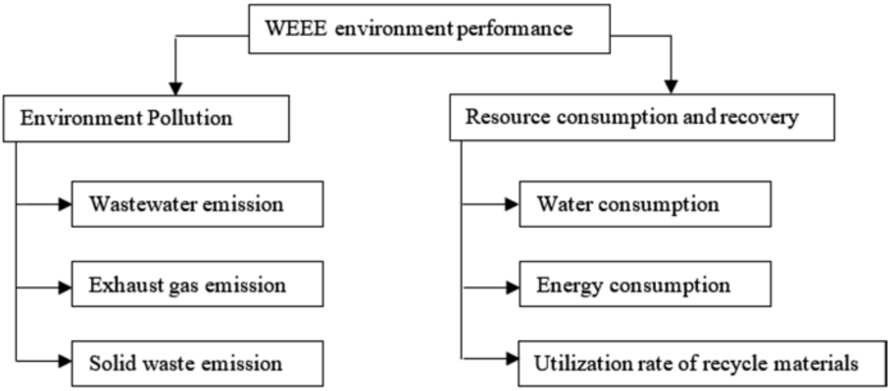

Fig. 3.2 E-waste environmental performance

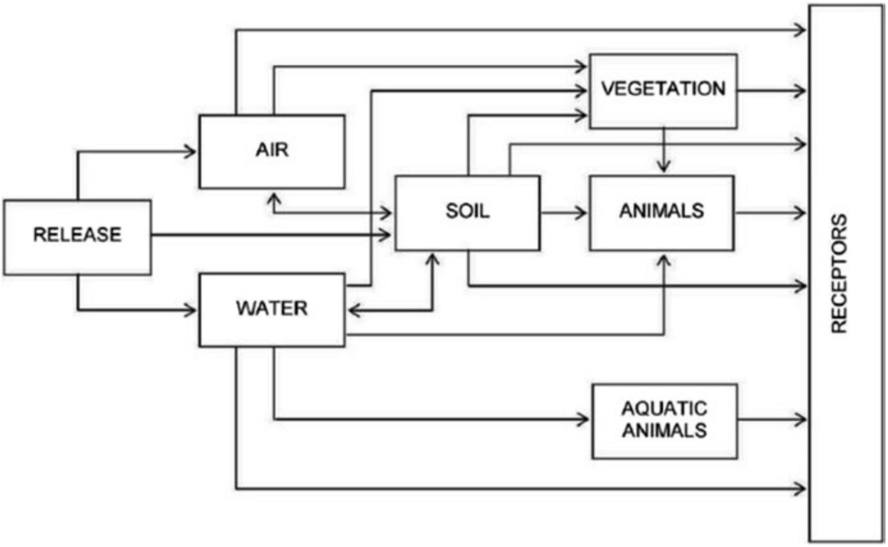

Fig. 3.3 Generic environmental pathways and compartments [31]

contamination release to any route, either air, water, or soil, indirectly influences humans. The burning process, for example, either in incineration process or open burning, releases plenty of contaminants in the atmosphere while the residue contaminates the soil and the water. It is essential to regulate the contaminant released to the environment as the consequences are disastrous [32]. Possible environmental and occupational risks from various solid waste systems can be found from Table 3.8.

Table 3.8 Possible environmental and occupational risks from various waste systems

Computer/e-waste component	Process witnessed in Guiyu, China	Potential occupational hazards	Potential environmental hazards
Dismantled printed circuit board processing	Open burning of chips cut for the removal of final metals	Tin, plum, brominated dioxins, beryllium, cadmium, and mercury inhalation cause toxicity for staff and neighboring communities	Tin and lead contamination of immediate environment including surface and groundwaters.
		Irritation of the breath	Brominated dioxins, beryllium, cadmium, and mercury emissions
Cathode Ray Tubes (CRTs)	Breaking, removing, and dumping copper yokes	CRT glass cuts in case of implosion silicon	Pb, Br, etc. leaching into groundwater, discharge of toxic element P.
		Cadmium or other metals inhalation or contact with phosphorus	
Toner cartridges	Use of paintbrushes to recover toner without any protection	Respiratory tract irritation	Emission of cyan, yellow, and magenta toners with unknown toxicity
		Carbon black possible human carcinogen	
		Exposure of cyan, yellow, and magenta toners with unknown toxicity	
Printed circuit boards	De-soldering and removal of copper chips	Tin and lead inhalation	Air emissions of the same substances
		Possible brominated dioxin, beryllium, cadmium, mercury inhalation	
Secondary steel or copper and precious metal smelting	Furnace recovers steel or copper from waste, including organics	Exposure to dioxins and heavy metals	Emissions of dioxins and heavy metals
Plastics from computer and peripherals, e.g., printers, keyboards, etc.	Shredding and low temperature melting to be reutilized in poor grade plastics	Probable hydrocarbon, brominated dioxin, and heavy metal exposures	Emissions of brominated dioxins and heavy metals, and hydrocarbons
Computer wires	Open burning to recover copper	Brominated and chlorinated dioxin, polycyclic aromatic hydrocarbons (PAH) (carcinogenic) exposure to workers living in the burning works area.	Hydrocarbon ash with PAH is released into the air, water, and soil.
Miscellaneous computer parts encased in rubber or plastic, e.g., steel rollers	Open burning to recover steel and other metals	Hydrocarbon, including PAHs and potential dioxin exposure	Hydrocarbon ashes, including PAHs discharged to air, water, and soil

(continued)

Table 3.8 (continued)

Computer/e-waste component	Process witnessed in Guiyu, China	Potential occupational hazards	Potential environmental hazards
Chips and other gold-plated components	Chemical stripping using nitric and hydrochloric acid along riverbanks	Acid contact with the eyes, the skin may result in permanent injury.	Hydrocarbons, heavy metals, brominated substances, etc. are released immediately into rivers and banks.
		Inhalation of mists and fumes of acids, chlorine, and sulfur dioxide gases can cause respiratory irritation to severe effects, including pulmonary edema, circulatory failure, and death.	Acidifies the river destroying fish and flora

3.2.2 Effect to Soil

In the majority of cases, soil contamination is caused by illegal recycling facilities with inadequate equipment and a disregard for environmental impact. The pollutant's type varies depending on the type of material recycled on the premises. Heavy metals have been observed in the soil of a WEEE dismantling field in Bangkok that has been in use for over 30 years. This place was used to dismantle items like CRT monitors, air conditioners, refrigerators, and printer toners. The pollutant emerges from swept and dumped WEEE components and scraps on empty land and near the side of the road to be repositioned later [33]. It is also found that the concentration of the heavy metals is significantly higher for soil samples collected at the dismantling area compared to the adjacent residential area.

Samples of soils and sediments revealed high levels of DBDPE, BTBPE, DPs, HBB, BEH-TEBP, and OBIND in analyzed FRs at Bui Dau (BD), a recycling village in the province of Hung Yen in the North part of Vietnam. Both evolving FRs were found in samples from nearby recycling sites at higher concentrations. These findings show that e-waste items containing these FRs are present at this EWR and released from recycling practices to the atmosphere [34]. The state of the soil has a direct impact on agricultural activity because crops absorb nutrients from the soil.

In the small town of Longtang in northern Guangdong province with 100,000 residents, where the paddy field and vegetable farm co-exist with WEEE processing premises, the content of heavy metals (Cd, Cu, Pb, and Zn) was found 4 times greater than the background value in the soils of Guangdong province. Moreover, the concentration of certain heavy metals exceeds the permissible concentration for agriculture use [35]. This condition has had an effect on the heavy metal content in the vegetable farm, with Cd and Pb concentrations of 4.7 and 2.6 times the maximum allowable levels, respectively. It was also discovered that the concentration of heavy metals in the leaves is higher than in the roots. Chlorinated and brominated

DRCs (dioxin-related compounds) were found in abundance in the soils of Agbogbloshie's open E-waste burning areas. PCDD/Fs (Polychlorinated dibenzo-*p*-dioxins/dibenzofurans) concentrations ranged from hundreds to thousands of nanograms per gram, while PBDD/Fs concentrations ranged from hundreds to thousands of nanograms per gram (dry weight). These levels are among the highest found in soils from informal e-waste recycling sites to date [36].

3.2.3 Effect to Water

3.2.3.1 Groundwater

Groundwater is also influenced by the incorrect and inappropriate disposal and/or discarding of E-waste as heavy metals (e.g., Cd, Ni, Pb, etc.) and other persistent chemicals leach from landfills and illegal dumpsites into groundwater tables. As a result, it causes negative effects to the people and animal life for many miles around. The groundwater is easily affected as it is normally being recharged through the rain that seeps through the layers of soil. The top layer soils that were affected by informal recycling activity were the main supply of the contaminant in groundwater. Groundwater is also being recharged by the surface water, which can be a disposal area for unsalvageable WEEE and from the recycling process. The elevated concentrations of contaminants such as heavy metals are also influenced by other factors such as the acidity of the water and the content of organic carbon that helps in the immobilization of heavy metals. The immobilization of heavy metals is also influenced by their ready sequestration by the abundant reactive sites affected by plant-induced organic matter in soil and/or to their precipitation properties under a circumneutral pH condition in the porewater [37].

A case of recycling and disposal of e-waste leads to high levels of heavy metal in the agricultural region of Mandoli surface land, plants, and soil. The Mandoli industrial area is one of India's most important informal e-waste recycling sites, with about 60–80 small- and medium-sized businesses recycling printed circuit boards, batteries, cables, and CRTs. The concentration levels of heavy metals in the water sample collected from the industrial area were recorded to be above the maximum allowable concentration. However, the levels of heavy metals in the residential water sample were observed within the desirable range limit. Therefore, it can be concluded that the water samples collected from the industrial zone are unacceptable for drinking purposes. It is also found that the heavy metals which exhibited concentrations above the permissible limit in water samples are the main metal components of WEEE [38].

3.2.3.2 Surface Water

Chemical methods used to remove precious metals from electronic products, such as gold, have an effect on surface water in particular. These methods usually use acids and other harmful chemicals to leach or remove valuable materials from less valuable materials, such as plastic, which are then released into local water bodies such as streams, wetlands, and rivers if not properly handled or controlled. Acidification and toxification of water can spread miles away from a recycling site through these pathways, posing a variety of threats to public and ecosystem health.

In certain areas, even with the discontinuation of the illegal WEEE premises, the effect of the improper handling still can be found in the water bodies nearby. In Longtang, Guangdong province in China, an abandoned e-waste recycling site, the water in the pond was heavily acidified and polluted with heavy metals, reflecting the effects of the previous e-waste recycling operation. The heavy metal found with an elevated concentration in the streams includes Cr, Ni, Pb, Cd, Cu, and Zn. For the past decades, the water used for acid-washing E-waste has been dumped directly into a local drain, ultimately ending up in wetlands, causing significant acidification and heavy metal pollution. The unsalvageable e-waste part of the WEEE was buried in a landfill site near the stream, allowing acidic compounds and heavy metals to leach into the stream after runoff. As the pond water is used for irrigation for agriculture purposes, the crops in the farm fields will become polluted, potentially impacting human health [39].

3.2.4 Effect to Air

Air pollutant production is usually linked to open incineration operations. Examples of free burning applications include component isolation, solder reclamation from PCBs, melting of plastic parts before open dumping, and copper recovery from electronic cables. The release of dangerous compounds into the atmosphere from the open burning of WEEE has a strong environmental influence, with an indirect effect on the deposition of toxins into the soil, sediment, or water.

The pollutant that can be released from plastic recycling activities includes PAHs (polycyclic aromatic hydrocarbons), PCBs (polychlorinated biphenyls), PBDEs (polybrominated diphenyl ethers), and PCDDs/Fs (polychlorinated dibenzo-*p*-dioxins and dibenzo-furans) that are known with high toxicity character. Unscientific methods, together with improper facilities, lead to excessive exposure of these toxic substances to the recycling employee. A plastic recycling area located in Guiyu town in China has been polluted by PAHs sourced from recycling activity sites such as dismantling workshops, typical recycling workshops, and waste incineration fields [40]. These contaminants, especially benzo-a-pyrene (BaP), which is assigned the maximum carcinogenic potential factor of 1 (toxic equivalent factor, TEF), may lead to lung cancer.

3.2.5 Effect to Human

The hazardous substance originated from WEEE disposal can be found in elevated concentrations in the human body. The exposure can be direct for a worker in recycling premises or indirect for people who live nearby the premises. For example, the highest PBDE (Polybrominated diphenyl ethers) concentrations in human placenta tissue were found in Guiyu, a traditional e-waste recycling site in southern China, with the overall median nearly 15 times higher than studies in non-e-waste polluted areas and twice as much as another e-waste polluted area from Taizhou in eastern China, according to a report. Because of PBDE bioaccumulation and different bioavailability, high PBDE concentrations in Guiyu may mean that the health of vulnerable pregnant women and infants is likely to be harmed, as may lead to adverse physiological development in the fetus [41].

Residents of Vietnamese who lived nearby to EWRSs (informal e-waste recycling sites) were exposed to DRCs (dioxin-related compounds) released from informal e-waste recycling, according to the findings of a report by [42]. People who worked in the recycling industry in BD village were more likely to be exposed to PCDFs (polychlorinated dibenzo-*p*-dibenzofurans) and PBDFs (poly-brominated dibenzo-*p*-dibenzofurans), and ingestion of polluted dust was a common route of exposure. According to the findings, some milk samples from the EWRSs workers may have contained unidentified compounds with dioxin-like properties. By comparing the DRC profile in the milk of these women with the reported profile in house dust from the same site, dust ingestion was estimated to contribute most of the intake.

3.2.6 Climate Change

In general, recycling processes have a major potential for minimizing the emissions of greenhouse gases (GHG) due to less energy process usage. The main manufacturing methods for intermediate materials, such as aluminum (Al), necessitate a lot of energy to melt the raw material (i.e., bauxite). Since the scrap Al has high purity, recovering and melting secondary Al requires much less energy (as compared to bauxite). Lowering energy demand also means lower CO_2 emissions. A similar case can be made for many other recycling systems, such as glass, paper, plastics, and so on.

Additional waste classifications, such as old laundry machines, laptops, cell phones, and so on, will potentially have their GHG effect reduced dramatically by improving manufacturing processes. However, since most e-waste uses energy at the consumer level, the appliance's performance is also a consideration to consider when calculating the effect of GHG on electronic products over their life cycle.

3.2.7 Treatment Plan

The existence of dumping and recycling area for WEEE has been there since the first electric and electronic device was invented, and the fact that the EEE industries keep growing worsened the pollution caused by them. The establishment of legislation to regulate the disposal's approaches helps in minimizing the effect on the environment.

The idea of using biological treatment appears to offer a lot of chances in treating the polluted area. The most popular method to reduce the contaminant's concentrations in the soil is using the plant to use the heavy metal as nutrients. One of the findings from a study indicated that sunflower combined with Arbuscular mycorrhizal fungi could be used to reduce heavy metals stress and promote phytoextraction of heavy metals from highly polluted field soil due to WEEE recycling [43].

3.3 Waste Management

3.3.1 Policy and Initiatives

The legislation was enacted with three major aims: regulating hazardous substances in EEE and reducing the waste volume, prohibiting illegal WEEE trading, and improving WEEE management. The existence and extent of enforcement differ from country to country. According to reports, in 2019, 71% of the world's population is covered by legislation enacted by local governments, compared to only 44% in 2014 [7]. This positive trend is attributed to rising awareness of the value of specific WEEE laws, with an increasing trend in the number of countries developing specific legislation, policy, and regulations. Where, just 64 countries were protected by a particular law regulating WEEE in 2014, but that number increased to 67 countries in 2017 and 78 countries in 2019. The establishment of certain initiatives and agreements show the importance of the participation of all organization and country to ensure the holistic solution [7].

Stakeholders and policy-makers are always cornered between the fascinating chance of resource potential and the adverse effect of the pollutant originated from the WEEE [14]. It is necessary to look for an intercept point between the risk and chance. It is also noteworthy to understand that the recycling process, in general, cannot be considered as a sustainable approach, especially when an inappropriate and unscientific method is not available [21]. In certain cases, the recycling process is less preferred due to economic factors and a lack of technology.

Generally, four types of common management scenarios have been identified by [13], which are listed in Table 3.9. Based on the variations of the scenario summarized, it can observe a contradictory approach has been taken in a different region. Scenario 1 can be considered as well-managed WEEE flow, while scenario 4 is the worst.

Table 3.9 Common management scenario summarized by [13]

Scenario 1	• dedicated treatment facilities
	• follows statutory requirements provided by existing WEEE/WEEE-related legislation formally documented and collected WEEE
	• established WEEE collectors (municipal collecting points, EEE producers and retailers)
Scenario 2	• destined for landfill or incineration, depending on prevalent disposal methods
	• Consumers dispose of WEEE together with a non-segregated household waste
	• direct disposal of WEEE together with commingled household waste
Scenario 3	• not officially documented due to the absence of legal requirements
	• recycling of collected WEEE at specialist facilities, refurbishment, or exportation to developing countries
	• an unofficial collection of WEEE (waste brokers and dealers)
Scenario 4	• treatment methods are often basic and rudimentary
	• not regulated as there is absence, or no enforcement, of legislation
	• involves reuse, repair, and cannibalizing WEEE for parts
	• relating to WEEE management
	• collectors seek metal constituents within the WEEE
	• an unofficial collection of WEEE (waste brokers and dealers)

In brief, scenario 1 take part in a region with well-established regulation with the proper organization appointed to complete the collection and transport the waste to dedicated recycling facilities. These steps help in minimizing the waste transported to the landfill or incineration center. The existence of legislation may not be the sole factor to a well-managed WEEE. In fact, Scenario 4 (Table 3.10) may co-exist in the same region together with Scenario 1. Another factor, such as individual/organizational awareness and logistics, contributes to the level of rule's executions [2].

The Silicon Valley Toxics Coalition was established in 1982 in response to groundwater pollution in Silicon Valley. Toxic solvents from a Fairchild computer chip factory were released into over 100,000 homes in San Jose. Civilians both within and outside the factories developed cancer, fertility problems, and other diseases, and they banded together to fight back. Despite the fact that this campaign is not directly focused on WEEE, the issue has raised awareness in the global community about an unseen ongoing danger.

BASEL Convention on the Control of the Transboundary Movements of Hazardous Wastes and their Disposal was adopted in 1989 and came into force in 1992. It is specifically established to regulate the trading of WEEE from industrialized countries to less-developed and vulnerable nations [18]. There are 186 countries that signed the convention, which was initiated by the United Nations (UN) [44]. This convention contains the restriction or WEEE trading to the country that possesses no environmentally sound practices for managing the imported waste. Despite owning a well-defined legislative, the illegal trading of WEEE still abounds. Despite the fact that the illegal trade of WEEE has decreased since the establishment of the Basel Convention, illegal trading continues. A case study in Japan shows that the occurrence of illegal trading still can be found even with very strict laws

Table 3.10 Description of the global initiative on WEEE management [21]

Global initiatives	Task description and responsibilities
Silicon Valley toxics coalition, 1982	Worldwide efforts to foster human health and environmental justice have been made in the USA for a sustainable cause in response to rapidly rising high-tech industries.
Basel Convention, 1992	An amendment to ban the transport of waste from OECD to non-OECD countries could not be ratified but could not, therefore, be applied to restrict the cross-boundary movement of risky waste (including WEEE)
Basal action network, 1997	A global network for WEEE exports and illicit dumping to achieve a safe and sustainable solution
Global e-sustainability Initiative, 2001	To guarantee the discarding of WEEE, including their reuse and recycling, is less dangerous
Mobile phone partnership initiative, 2002	A proposal program initiated by 12 mobile phone manufacturers seeks for more sustainable management of the EoL mobile phones
SECO-EMPA e-waste program	The Swiss Federal Laboratory for the Testing and Research of Materials (in cooperation with local collaborators for improvement of the WEEE recycling system and the exchange of information with global partners)
The goods electronic networks, 2003	A coordinated research center for international companies in the field of electronic goods for more sustainable development
E-stewards pledge program, 2003	Founded mainly in North America and now operates worldwide. They seek to recycle electrical products responsibly without requiring jail labor.
Electronic product environmental assessment, 2003	Social non-profit organization; operated by members from industry, the environment, academia, tradesmen, recyclers, and governmental authorities; registering greener EEE in 41 countries/ regions
Solving the e-waste problem, 2004	A digital WEEE management and supply chain information sharing forum
Partnership for action on computing equipment, 2008	A cooperation association on the management of EoL computer equipment for public authorities, industry, NGOs, and academia
Secretariat of the Basel Convention and ITU Agreement, 2012	WEEE collection and recycling by green ICT standards, global collaboration, and the development of capacities

enforced [8]. The operating expense in the origin country, informal and unrecorded collection are a few of the main factors that encourage illegal WEEE trade [8, 45]. E-waste is transported into many developed countries (e.g., Benin, Cote d'Ivoire, Liberia, Kenya, South Africa, Uganda, Senegal, Philippines, India, China, Malaysia, Indonesia, Vietnam, Bangladesh, Nigeria, Pakistan, Bhutan, Nepal, and Sri Lanka) without adequate planning or strategic management. As a result, the majority of these wastes end up in urban landfills or warehouses of rudimentary recycling operations [15].

A concept of Extended Producer Responsibility (EPR) has been applied in Europe where the responsibility of recycling and collection of WEEE belong to the producer placing the items on the market [14, 44]. These parties which are responsible for the processing of WEEE are the organization appointed by the government and funded by the technology producers and importers. While the strategy has a potentially positive effect on the rate of collection and recycling, the reality is very different. EPR regulations sometimes fail to deliver the desired effects or have unintended consequences [46]. It is suggested that subsidies can provide good motivational support for the responsible managing WEEE organization. However, the capability to allocate such funds is minimum for a certain country. A model developed by [47] found that the subsidy alone is not adequate to support the WEEE management system in Indonesia. This is due to the high operation cost; hence the government contribution fund is important to ensure the sustainability of the system. Another study by [8] portrays operational cost as the main factor that encourages illegal WEEE trading.

The legislation established in Japan is constituted of two components: the first is the Law for the Promotion of Effective Utilization of Resources (LPUR), and the other is the Law for the Recycling of Specified Kinds of Home Appliances (LRHA). LPUR is focusing on establishing a recycling-based economic system by reusing sections of collected goods like computers, improving collection methods, and introducing new waste-reduction and product-life-extension initiatives. In contrast, the LRHA requires home appliance manufacturers and retailers to ensure proper waste management and resource efficiency [44]. Another complementary law regarding WEEE management, known as the Law for the Promotion of Recycling of Small Waste Electrical and Electronic Equipment (PRSWEEE Law), has been established since 2013 [8]. This legislation focuses on a legal recycling scheme that seeks to recover more energy from the urban mine of small-sized WEEE by implementing end-of-life product export control since the transport of these solid waste out of the country is thought to have a detrimental effect on the domestic recycling system. However, the inadequacy of economic incentives for scrap dealers to sell certain waste such as mixed metal scrap to domestic recyclers leads to the exportation of such scrap to foreign countries. This situation is also partly due to the lack of a well-defined measurement system for judging the controlled hazardous characteristics [8].

China is the largest WEEE producer, having generated 10.1 million tons of WEEE in 2019 because of two factors which are: (1) China is the most populous country in the world, and (2) it has a robust EEE manufacturing industry. There is three key legislations in force in China which are Law on the Promotion of Cleaner Production (2002), Law on the Promotion of Circular Economy (2008), and Law on the Prevention of Environmental Pollution from Solid Waste [48]. Promotion of Cleaner Production (2002) facilitates waste management prevention principles during the design and development of EEE, as well as their end-of-life treatment. This legislation also promotes reduction of the use of hazardous and toxic substances in electronic equipment and reduces emissions caused by their manufacturing process while the Law on the Promotion of Circular Economy (2008) focuses on the prevention of pollution caused by the storage, transport, disassembly, recycling, and disposal of WEEE. It is also emphasized that WEEE must be obtained across various channels and processed by approved recycling companies, according to the regulation. Law on the Prevention of Environmental Pollution from Solid Waste (2004) aims to minimize WEEE volume, increase the reutilization rate for discarded EEE, and improve e-waste recycling standards [44]. With all the regulations in place, the informal sector has been dramatically declining due to stricter controls from China's new environmental law. On the other hand, China's WEEE management practice is up against a number of challenges in order to achieve the country's sustainability goals, which include being economically viable, environmentally sustainable, and socially responsible. For example, ineffectively applied legislation and the competitiveness of informal recyclers are two well-known obstacles [49]. The government's subsidy allocation has acted as a catalyst in the management of environmental emissions where, at the same time, by taking advantage of government incentives, formal recyclers have gained profound profits [50].

Hazardous waste management strategies were established in Malaysia in 1989 in response to the rapid growth of industrial activities, which resulted in a variety of waste products and materials. Minimizing the environmental and health threats raised by such diverse hazardous wastes necessitates the successful execution of policies and strategies. In Malaysia, the discharge of the Environmental Quality (Scheduled Wastes) Regulations 2005, which replaced the annulled Environmental Quality (Scheduled Wastes) Regulations 1989, has recognized e-waste as a scheduled waste under the code SW110. The specified e-waste, such as waste from batteries containing heavy metals, lead-acid batteries, and fluorescent lamps, are coded as SW103, SW102, and SW109, respectively [51].

Malaysia is projected to produce 53 million pieces of e-waste by 2020, necessitating the introduction of a proper mechanism to manage dangerous substances [16]. The Malaysian government responded by drafting the Environmental Quality (Household Scheduled Waste) Law, which is currently being reviewed by the Attorney General's Chambers [52]. WEEE is currently classified as scheduled wastes according to the Regulations 2005 on Environmental Quality. These provisions state that no individual shall be able to dispose of WEEE at landfills; however, WEEE shall be recycled and recovered in controlled locations or at approved locations, and if necessary, disposal shall be done only in a designated location and shall be conducted in an environmentally friendly way. Malaysia has licensed 18 full recuperation facilities and 128 partial recuperating installations through its Department of Environment (DOE) [51]. These regulations state that no e-waste can be disposed of in landfills, that e-waste must be recycled and retrieved at prescribed or approved facilities, and that disposal may take place only at prescribed facilities and in an environmentally sound manner.

3.3.2 Collection

WEEE is not an ordinary waste that can be treated as common municipal waste owing to the material it contains. Therefore the necessity of its collection method is positioned as one of the major factors in the efficiency of WEEE management, together with the proper legislation and recycling activities [10]. The collection system of WEEE consists of the collectors and logistic factors. The collection and recycling rate varies depending on the region. The European country has the highest rate of collection and recycling at 42.5%, while the African country has the lowest rate at 0.9%. Asia, the Americas, and Oceania country have the collection and recycling rate at 11.7%, 9.4%, and 8.8% accordingly (Fig. 3.4). The exceptional performance of WEEE management in a European country is due to the availability of a defined framework. In fact, a certain country such as Finland and Sweden has an even higher recycling rate [13].

In Poland, as an example, the collection of WEEE can be done in three ways which are collected by the collector in residence, take back service by the seller after the consumer purchases new items, and the end-user can bring the obsolete item to any WEEE seller [53]. The latter approach reduces the operational cost for the collector, at the same time, increases the WEEE volume collection. The convenience of the collection system has been known as good support in whole WEEE management [10]. In many studies, convenience factors are statistically significant towards the positive attitude to deliver or segregate the waste [54]. Conveniences can be divided into two groups based on the executor, either the end-user or the collector. For end-user of EEE, aspects such as the distance of the collection site that affects the time needed and cost for end-user to deliver their WEEE. The existence of containers for small-sized WEEE such as a battery, watch toys, and mobile phones assists in creating more convenient collection activities.

On the collector side, operational costs, including logistics of collections, schedule of collection, number of vehicles and employees, etc., play a significant part in

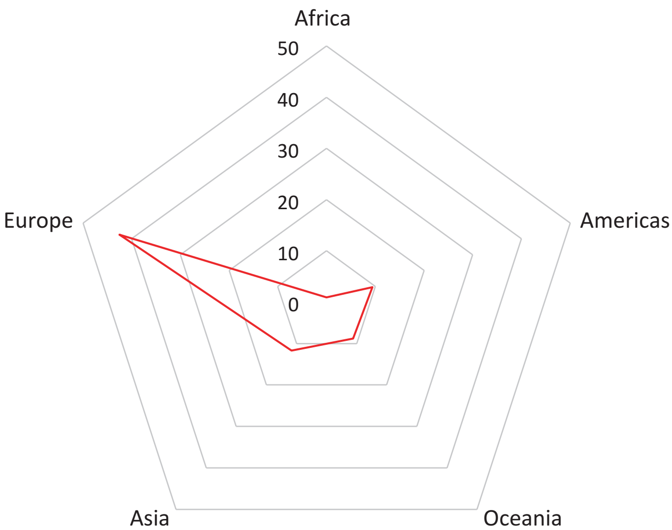

Fig. 3.4 Collection and recycling rate of WEEE [7]

the efficiency of the collection process. A study by [53] has compared three types of collection methods which are (1) moveable collection by vans that are travelling along all streets and roads in collection zones; (2) stationary collection—which includes the containers placed in the vicinity of households; and (3) transportation of the e-waste by residents to the municipal collection center. A mobile collection with the least environmental impact and the lowest overall cost is the preferred process. Transportation of waste by citizens to municipal centers is the least sustainable approach in this assessment, where residents are responsible for the collection costs in this situation. The most effective approach is to collect the e-waste at the time of delivery of new equipment, so there is no extra cost or pollution because the delivery vehicle eliminates the unnecessary WEEE. All companies that distribute EEE to customers' homes should make this option available. Small-sized WEEE is always treated as non-WEEE waste that is discarded in the container that is prepared for municipal solid waste (MSW) and ends up landfilled and incinerated [7] in a high-income country.

3.3.3 Recycling and Recovering Technology

Big household equipment (i.e., ovens, refrigerators, laundry machines) account for more than 40% of the generated e-waste. However, other products such as TVs (over two million discarded per year), IT equipment (primarily computers), small household appliances (i.e., hairdryers and kettles), digital watches, electrical instruments, medical devices, and electronic toys account only for considerable amounts of the generated WEEE.

A standard TV consists of 6% metal and 50% glass, while a stove/oven consists of 89% metal and only 6% glass. Other materials such as ceramics, plastics, and precious metals were among the other items discovered. WEEE recycling poses a variety of health hazards due to this diverse combination of products and materials, some of which are dangerous (including As, Cd, Hg, Pb, and some flammable retardants), must be carefully handled. Exposure to contaminants released during manufacturing, for example (such as Hg released from fluorescent tubes, Pb and phosphorous pentachloride (Cl_5P) as a result of breaking cathode ray tubes). It is important to emphasize that if appropriate steps are taken to monitor mercury and lead exposure, then exposure to other dangerous substances should be properly monitored as well. The exact care of WEEE differs significantly depending on the form of WEEE and the technology used. Some of the available treatment facilities employ "large-scale shredding technology," while others employ a disassembly process that can be either automated, manual, or a combination of both.

3.3.3.1 Technology Feasibility and Organizational Requirements

Due to the wide variety of products, from electrical equipment like hairdryers to fully automated systems like computers and mobile phones, WEEE is one of the most difficult wastes to handle [55]. Several primary WEEE management issues have been described as operational criteria for successful WEEE recycling.

3.3.3.1.1 Facilities for Collection

Collection facilities are important for the collection and separation of different types of WEEE for waste management and recycling processes. The WEEE should be defined in different categories, according to the European Environment Agency (EEA) [55].

Table 3.11 presents the categories of WEEE and the challenge in the recycling process [56].

3.3.3.1.2 Dismantling and Separation

It is the first and most critical step in reducing WEEE volumes and emissions from WEEE treatment. Several steps can be taken to boost the situation where a significant percentage of the e-waste is incinerated or landfilled. Dismantling tools shall be created and enhanced to automate the disassembling method and develop the segregation of the materials in the first stage. Besides that, recyclers should be equipped with information about where parts containing hazardous substances can be found and how to identify them. When the input is not dismantled, the shredder method is deemed as the highly difficult stage in the pre-treatment sequence. Despite the fact that this method is intended to make the segregation of material easier and simpler (ferrous, non-ferrous, and plastic), no pure fractions are generated, resulting in large amounts of hazardous substances being spread throughout both fractions. This causes issues in the recycling facilities that follow. As a result, efforts are needed to reinforce the process technology and to provide alternatives. Because

Table 3.11 Categories of WEEE and the challenge in the recycling process [56]

Categories	Remarks
Lighting equipment	To allow for mercury recovery.
Large white goods	The ferrous, non-ferrous, and plastic fractions can be recycled immediately after removing any capacitors that may contain PCB.
Refrigerators and freezers	To allow for separate CFC treatment.
TV sets and monitors	To allow for special treatment of circuit boards and parts containing flame retardant.

shredder waste is not recoverable, it can be incinerated after further processing in well-regulated plants or used for energy recovery in plants with high-standard flue gas cleaning systems. Before the shredding, easily accessible sections should be removed to reduce the amount of shredder residues.

3.3.3.1.3 Improving Disposal Methods

Although a large proportion of the e-waste is still handled in municipal waste incinerators (MWI), a growing volume is processed for recycling in industrial facilities. The required abatement technologies should be implemented in these facilities.

3.3.3.2 Recycling and Recovering of Metal

Iron and steel are the weightiest elements of WEEE, followed by plastics. As can be illustrated, almost 50% of the weight of WEEE are iron and steel, which are the most used commodity in electrical and electronic systems. Other materials such as non-ferrous metals and precious metals account for about 13% of the total weight of the e-waste, with glass accounting for about 5%. The recycling and recovering of metal can be classified into two categories: a traditional method and advanced technologies. Some of the traditional practices which are employed to recover and recycle metals from the produced WEEE include (1) hydraulic shaking bed separation, (2) incineration process, and (3) acid leaching process. However, the innovative methods that are employed nowadays to recycle metals from the disposed of e-wase may include the following: electrochemical technology, bioleaching, mild extracting technique, pyrometallurgical method, bio metallurgical technology, supercritical approach, vacuum metallurgical technique, ultrasound technology, and mechanochemical method.

3.3.3.2.1 Conventional Approaches for Recycling of Metals from E-waste

The conventional techniques which are utilized for the recycling of electronic/electrical waste mainly included: (a) incineration, (b) acid leaching process, and (c) hydraulic shaking bed separation.

Incineration Process

Waste incineration is the practice of burning waste materials (usually burnable with high calorific value and low water content) in a furnace at high temperatures ranging from 750 to 1100 °C. The main final products generated from incinerators are ash, heat, and flue gas. Incineration of waste can generate power by burning the waste that contains carbon content. The incineration process has the potential to manage waste materials with great efficiency. It can reduce the waste volume up to 90% and waste mass by 75% with simultaneous heat and electricity generation. The energy efficiency for heat and electricity produced from waste is about 80% and between 20% and 30%, respectively. The incineration process is normally performed throughout two processes: (a) grate or (b) fluidized bed combustion. The grate combustion process uses fuel to burn the waste as it moves through the first grate. The complete combustion occurs in the second grade. Whereas in the fluidized combustion process, the fuel is combined and mixed with sand to improve combustion and enhance combustion efficiency. After the combustion process, the generated flue gas is cleansed of dioxins, acid gases, and heavy metals.

The incineration of E-waste is combusted immediately in the furnace. The furnace includes black copper by weight in the range between 70% and 85%. This black copper is oxidized until it is decreased in the anode furnace in the converter. Copper from the retrieved anode can be further purified with other elements such as Fe, Ni, and Zn in an electrolyte of H_2SO_4 [57].

Hydraulic Shaking Bed Separation

In the past, it was commonly utilized for the recycling of metals from waste printed circuit boards. This method will produce crude copper particles. However, this approach creates a lot of wastewater and residues [58]. Wastewater and residues can cause significant secondary contamination if not treated properly. In addition, most metals other than copper are difficult to recover. Moreover, materials such as "non-metal materials" cannot be recycled.

Acid Leaching Process

Acid leaching is a traditional hydrometallurgy method for recovering metals [59]. Cu, Pb, Zn, and other metals are extracted from WEEE using a leaching solvent of (HNO_3/HCl/$HClO_4$). In the previous years, other solvents such as "nitric acid" were combined with "hydrochloric acid" to make aqua regia. This "regia" can then be utilized for violent and non-selective ingestion of base and precious metals (Zn, Pb, Cu, Ag) from e-waste [60–62]. Due to the stability and selectivity of the dicyanoaurate complex, cyanide has been utilized for over a century to leach precious metal Au. Nevertheless, when cyanide is used poorly as a "leaching agent," it can have a significant concern, mainly due to its toxicity, which can trigger worker safety and environmental issues.

3.3.3.2.2 Unconventional Approaches for Recycling of Metals from E-waste

These old techniques stated above are not only ineffective, but they are also particularly harmful to the climate. Hence, some innovative recycling methods have been proposed in recent years, based on conventional technologies, and have made substantial progress.

Pyrometallurgical Technology

Pyrometallurgical science has made substantial progress in terms of the recovery and disposal of pollutants. Dismantling, smelting in a plasma arc oven, drossing, sintering, freezing, and high-temperature gas reactions are just some of the steps pyrometallurgy can take. Crushed metal scraps (both base and precious metals) are combusted into a heating furnace, and the chemical reaction or fire volatilizes the metals as impurities are converted to slogs. WEEE requires mechanical-physical pre-treatment, which involves removal of major parts, scratching processes for the reduction of sizes, part release, and so on.

The enriched metals are melted to form coarse metal lingoes in the furnace. The most frequent method of pyrometallurgy is the melting process. The two most common and commonly used smelting methods are bath smelting and flash smelting. Smelting by flash uses gas to allow autogenous conditions. Nevertheless, the roasting and smelting steps are the basis for bath smelting, and the reaction takes place in a molten bath comprising melts and slag phases. Further, bath smelting is based on roasting and smelting, and in an injective pool of both melts and slag phases the reactions take place [63]. The conversion process is the next step. Matt can be achieved by blowing air from tuyeres from the conversion unit in copper converters. This step will convert copper sulfide to metallic copper by oxidizing iron sulfide. The final process involves refining units in reverberatory or rotary furnaces to obtain high purity copper [64]. Figure 3.5 depicts the pyrometallurgical method of recycling copper in WEEE.

Mild Extracting Technology

Both new and modified hydrometallurgical technologies have become an attractive topic in recent years. Such methods are better suited to metal recovery or pre-treatment, are easier to monitor chemical reactions, and produce less waste than pyrometallurgical technology [65]. Any mild hydrometallurgy leaching agents have been suggested, including chlorinated leaching, ammonium leaching and non-cyanide leaching agents Au [66].

Biometallurgical Technology

In mineral processing, the biometallurgical technique is commonly used as an alternative metal recovery method from low-grade ores and concentrates [59]. However, several of the implementations for biometallurgy for WEEE remediation are still on the lab scale. The two main biometallurgical fields for metal recovery are bioleaching and biosorption. From the latest laboratory-scale findings, bioleaching is potentially viable with the use of a bacterial-assisted reaction to remove basic metals such as Cu, Ni, Zn, Cr and precious metals, like Au, Ag from WEEE. Bioleaching by heavy metals has a significant role to play in acidophilial bacteria such as Acidithiobacillus, Acidithiobacillus Thiooxidans and Leptospirillum ferrooximum and Sulfolobus [67, 68].

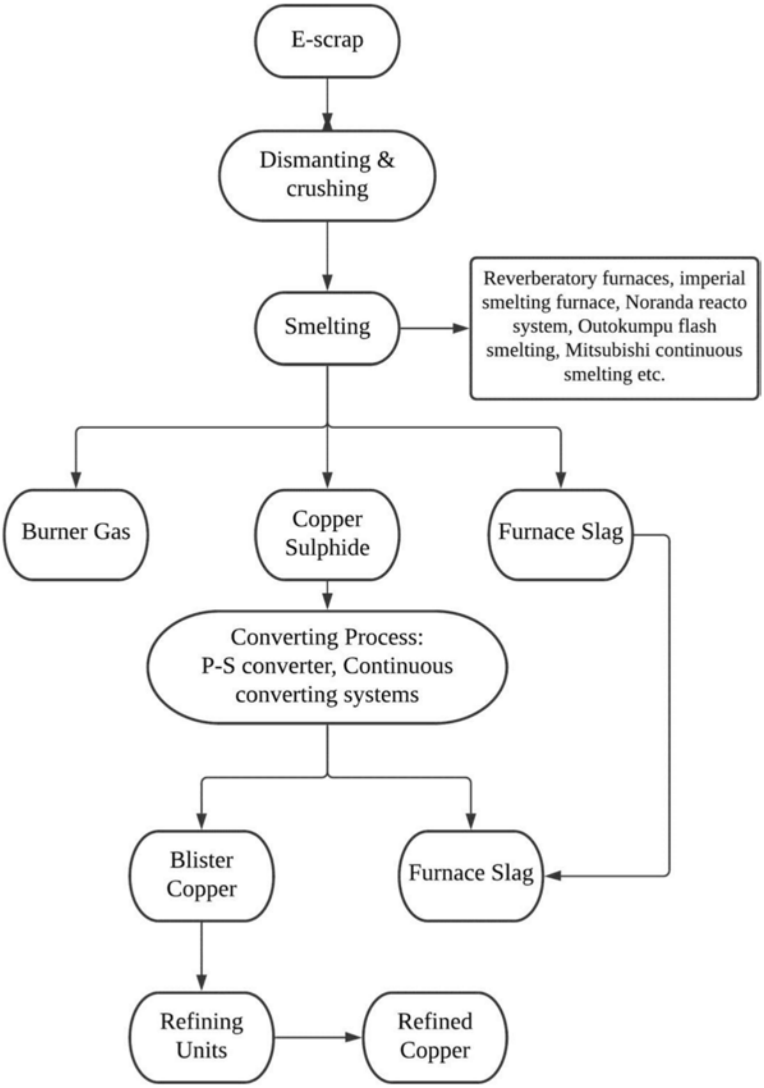

Fig. 3.5 Diagram showing the flow sheet for the recycling of copper in E-waste using pyrometallurgy processes [28]

Wang et al. [69] have employed bioleaching practices in order to extract the heavy metals from waste printed circuit boards. Acidithiobacillus ferrooxidans and Acidithiobacillus thiooxidans bacteria were grown and acclimatized in waste printed circuit boards prior to use as bioleaching bacteria for the purpose of dissolving metals. The findings of the study demonstrated that all ratios of Pb, Zn, and Cu were soluble in the printed circuit boards leaching solution. Printed circuit board concentrations should be held between 7.8 and 19.5 g/L at all times. Cu dissolution concentrations by a pure culture of Acidithiobacillus ferrooxidans, pure culture of Acidithiobacillus thiooxidans, and mixed culture of Acidithiobacillus ferrooxidans and Acidithiobacillus thiooxidans at 0.5–1.0 mm of sieve fraction at 9 days of leaching time are 99.0%, 74.9%, and 99.9%, respectively, under 7.8 g/L of printed circuit boards.

Karwowska et al. have utilized a culture of sulfur-oxidizing bacteria and a mixed culture of biosurfactant-producing bacteria and sulfur-oxidizing bacteria. The researchers have investigated the possibility of bioleaching for the heavy metals (i.e., Pb, Zn, Ni, Cu, Cr, and Cd) from waste printed circuit boards. In both of the studied media, around 48% of Zn and 93% of Cd were completely dissolved. Nevertheless, in the acidic medium, Cu and Ni had a superior effect, with removal rates of 53% and 48.5%, respectively. Pb was withdrawn with just a small amount of success with less than 0.5%.

Biosorption

Biological absorption is a method that retains substances from solutions based on physicochemical and metabolism mechanism [70]. Some types of inactive or dead biomass material may also bind and accumulate metal ions of industrial wastewater and aqueous solutions due to their characteristics. In the field of biosorption by precious metals, biosorbents are produced from a range of microorganisms, including bacteria, fungi, and algae.

Mata et al. [71] have employed dead biomass of the brown alga "Fucus vesiculosus" to successfully recover Au(III) as metallic gold nanoparticles. The findings showed that Fucus vesiculosus, a brown alga, can retrieve and reduce the element Au(III) to Au (0). Results showed that the highest gold applications were achieved at pH values ranging from 4 to 9, with a peak at a pH value of 7.

Tasdelen et al. [72] used DEAE-cellulose, a popular biopolymer derivative, to investigate gold recovery from synthetically prepared diluted gold-bearing solutions of 50 ppm. The findings indicated that gold could be retrieved efficiently by utilizing large quantities of "DEAE-cellulose" (at DEAE-cellulose/Au weight ratios of 400 and above), with a recovery rate for gold of more than 99%. More information on recovery of precious and base metals using biosorption and bioleaching can be found from Table 3.12 [65].

Electrochemical Technology

The electrochemical process is an exciting technique that provides a novel approach for the recovery of e-waste bases and valuable metals due to its high environmental compatibility, high energy consumption, and low chemical use. Kim et al. [73] have developed a method for leaching metals from waste printed circuit boards by utilizing electro-generated chlorine. The "electro-generated chlorine" method has the advantage of leaking precious metals owing to its ability for high oxidation potential. Figure 3.6 illustrates the schematic graph of separate reactors that have an electrolytic cell for chlorine generation.

Table 3.12 Recovery of precious and base metals using biosorption and bioleaching [65]

Process	Microorganisms/adsorbent	Recovery rate (%)/ Max of adsorption quantity (mmol/g)
Biosorption	Fungi	
	Fomitopsis carnea	Au, 0.48
	C. cladosporioides strain 2	Au, 0.5
	Cladosporium cladosporioides	Au, 0.5
	Aspergillus niger	Au, 1
	C. cladosporioides strain 1	Au, 0.4
	Rhizopus arrhizus	Au, 0.8
	Algae	
	Dealginated seaweed waste	Au, 0.4
	Chlorella vulgaris	Au, 0.5
	Fucus vesiculosus	Au, 0.35
	Sargassum natans	Au, 2.1
	Chlorella vulgaris	Au, 0.5
	Others	
	Chitosan derivatives	Pt 3.2, Pd 3.5
	Thiourea derivative of chitosan	Pt 2.0
	Bisthiourea derivative of resins	Au 3.63
	Chemically modified chitosan	Au 3.4
	Bacteria	
	Desulfovibrio fructosivorans	Pd 1.0, Pt 0.17
	Streptomyces erythraeus	Au, 0.03
	Desulfovibrio desulfuricans	Pd 1.2, Pt 0.32
Bioleaching		
	Acidithiobacillus thiooxidans	Cu 98%
	A. ferrooxidans + A. thiooxidans genera Acidithiobacillus and Gallionella	Cu 96.8%, Al 88.2%, Zn 91.6%
	Acidithiobacillus ferrooxidans	Cu 81.6%
	Aspergillus niger	Cu, Sn 65%
	A. ferrooxidans	Cu 99%
	Sulfobacillus thermosulfidooxidans + Thermoplasma acidophilum	Cu 95%
	Thiobacillus thiooxidans + T. ferrooxidans	Cu, Ni, Al, Zn >90%
	Sulfobacillus thermosulfidooxidans + acidophilic heterotroph (AlTSB)	Ni 81%, Cu 89%, Al 79%, Zn 83%
	Penicillium simplicissimum	Al, Ni, Pb, Zn >95%
	Chromobacterium violaceum	Au 68.5%
	Acidiphilium acidophilum (ATCC 27807)	Cu 3.6%, Ni 86% Zn 40.8%
	A. ferrooxidans	Cu 99%

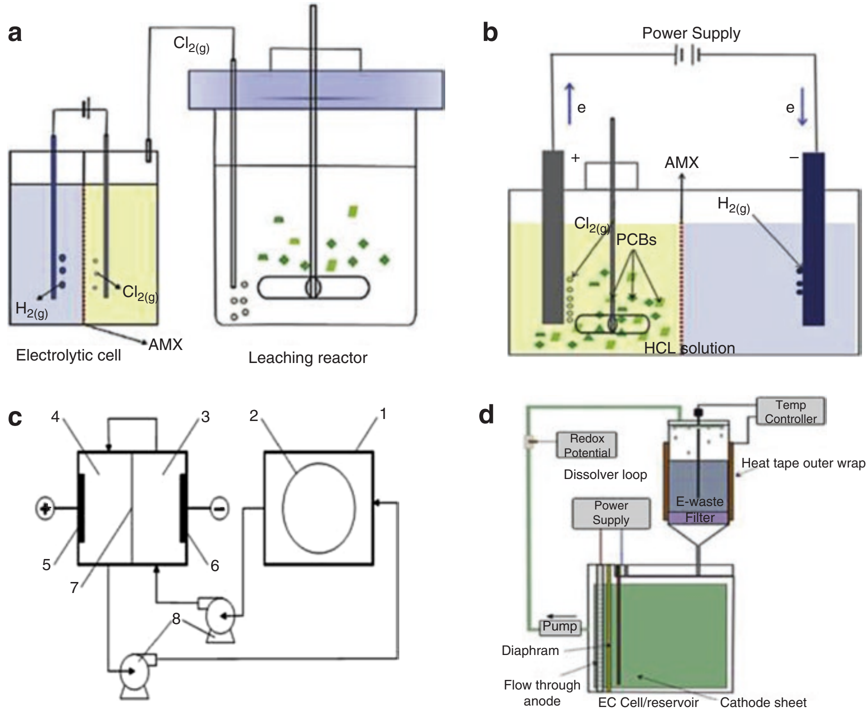

Fig. 3.6 (**a**) separate reactor composed of an electrolytic cell for the production of chlorine; (**b**) combined reactor composed of an electrolytic cell for the production of chlorine; (**c**) a mediated electrochemical oxidation; (**d**) electro-recycling system [73–76]

First of all, hydrochloric acid is applied into the leaching reactor, while the two cathodes and anodes were used. The following equation can be used to represent the anode reaction:

$$2Cl^{-} = Cl_2\left(\text{electrode surface}\right) + 2e^{-} \tag{3.1}$$

The contents of gold leaching improved with a rising temperature and initial chlorine concentration and were favorable even at low levels of acid. On the other hand, the leaching of copper was different in that it increased as the acid concentration and temperature fell. In a separate reactor, 97% copper was dissolved during the complete leaching process, with a gold recovery rate of 93%.

For the purpose of metal recovery rate, a hybrid reactor with a simultaneous generation of Cl_2 and metal was compared to a separated reactor that could flow and reuse ion chloride without additional addition, as illustrated in Fig. 3.3b [75]. Present density, temperature, and time rose in both reactors as Cu leaching. The dissolution was between 20% and 25% in the combined and separate reactors, with a continuously decreased copper leaching rate. The surface region of copper shapes CuCl with increasing leaching time (s). In addition, the combination copper reactor leaching efficiency was lower than that of the separate reactor due to the shift in electrode reaction.

A mediated electrochemical oxidation was proposed to recover copper and isolate a rich gold residue from waste circuit boards [74, 77]. The experimental setup for this is illustrated in Fig. 3.7c. Two different kinds of reactors were added together in series to the procedure. One was a split electrochemical reactor to restore the lixiviation solution, and the other was a laxative reactor with a performed turning drum to strip basic metals. The procedure was also carried out by sequentially combining two different reactor groups. One was a split electrochemical reactor to restore the leaching solution, and the other was the leaching reactor with a punched rotating drum to strip base metal.

Waste printed circuit boards were used to make an electrolyte that constituted 0.3 mol/L HCl and different varying concentration levels of $FeCl_3$. The electrochemical reactions are able to generate Cu in electrolytes like HCl and mediators like $FeCl_3$. Through anodic oxidation, Fe^{3+} can rejuvenate. The series connection of electrochemical reactors allows for simultaneous generation of Fe^{3+} and metal dissolution without the use of a leaching agent. The study has investigated the

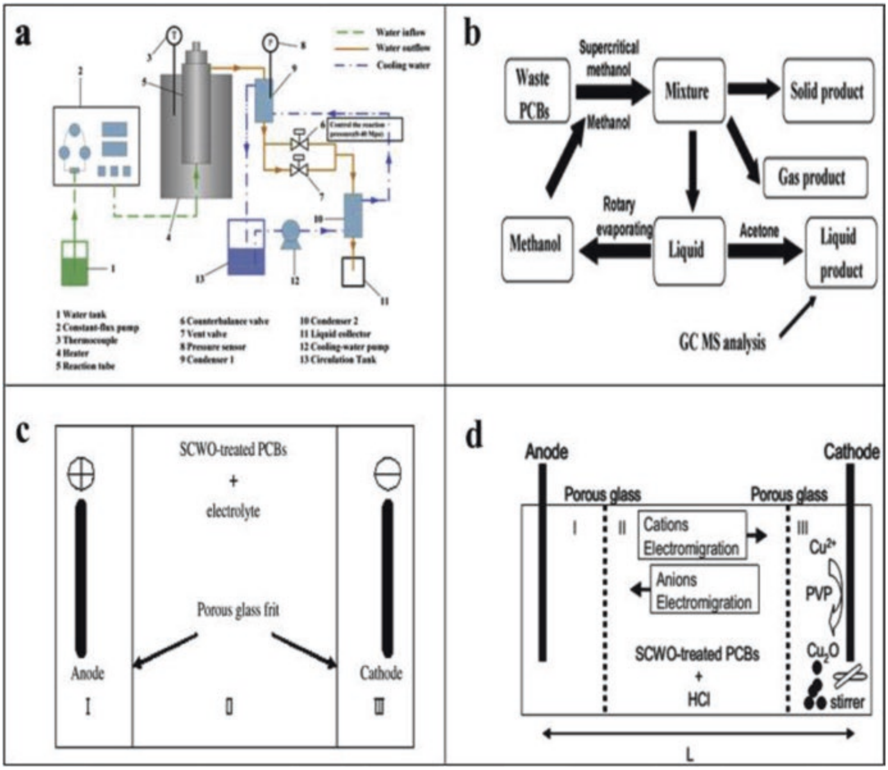

Fig. 3.7 (**a**) semi-batch-type SCW reactor; (**b**) SCM recovery phase; (**c**, **d**) combined SCW with EK phase [78–80]

dissolution performance, current efficiency, and basic energy consumptions of the process were all evaluated. At laboratory-scale leaching, a 99.04 wt.% high purity Cu was obtained with a current efficiency of 63.84% and specific energy consumption of 1.75 kW h/kg cooper. Metal powders from waste printed circuit boards were also analyzed using electro-oxidation leaching copper in sulfuric acid solution. The experiment used a leaching process with H_2SO_4, NaCl, $CuSO_4$, and air to try to recover base metal copper. Chloride ion was used as a complex agent, and Cu^{2+} and air were used as oxidants in the leaching system. The results revealed that the copper leaching rate could exceed 100%.

Supercritical Technology

Because of its special properties, such as low viscosity, strong mass transfer coefficients, high diffusiveness, and a high degree of solubility for organic products, supercritical technologies were recently applied to decompose organic polymers and recycle metals [78, 81, 82]. Supercritical technologies can be grouped as supercritical water, supercritical methanol, supercritical water and supercritical water oxidation. Supercritical water (SCW, Tc = 374 °C, Pc = 22.1 MPa) was used by [79] to decompose brominated epoxy resin (BER) from waste memory modules and recover environmentally friendly metals. The schematic diagram of the semi batch-type reactor is shown in Fig. 3.8a. The conditions of semi batch-type reactor are set up by temperatures at 350–550 °C and pressures at 25–40 MPa. The reaction times are maintained at 120–360 min and throughout the process without any use of the external catalyst. The findings revealed that under SCW conditions, BER could be decomposed quickly and effectively, with a metal regeneration rate of 99.80%. It is also feasible that the process mechanism was a free radical reaction.

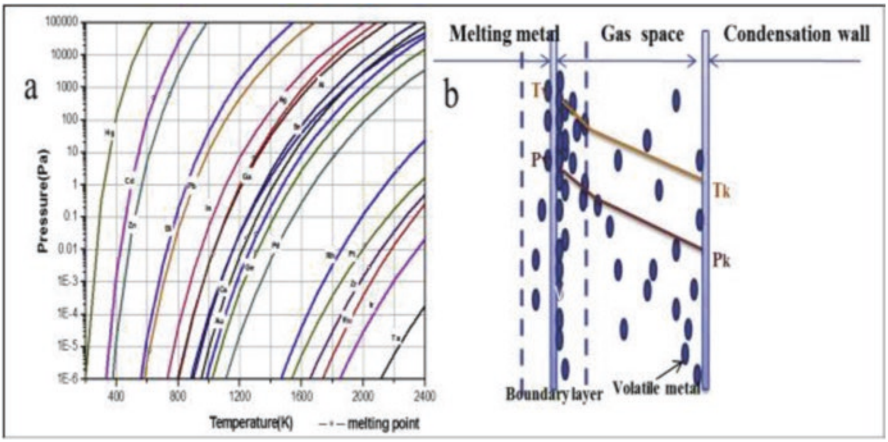

Fig. 3.8 (**a**) The transformation process of metals from melt; (**b**) relationship between the temperature of metals and the saturation pressure [28]

Xiu and Zhang [80] used supercritical methanol (SCM, Tc = 240 °C, Pc = 8.09 MPa) to recycle polymers and metals from waste printed circuit boards at the same time. The chemical recovery method from waste PCBs using supercritical methanol is depicted in Fig. 3.8b. Initially, the waste printed circuit boards were applied in the reactor with the necessary volume of methanol. The liquid-solid mixture in the products was filtered through a membrane filter (pore size of 1.0 m) after the reaction of SCM. When the waste printed circuit boards were effectively concentrated after SCM treatment, high concentrations of Cu (34%), Fe (7.9%), Sn (7.9%), Pb (6.3%), and Zn (2.6%) were contained in the majority of solid items. The solvent methanol was extracted using a rotary evaporator, followed by the oil and gas products.

A technology combining supercritical water oxidation (SCWO) and the electrokinetic process was also developed [78, 80, 83]. The printed circuit boards were pre-treated in supercritical water before being subjected to the electrokinetic process. First, the sample and distilled water were used in the SCWO treatment tests, and hydrogen peroxide (H_2O_2, 30 wt.%) was used as the oxygen source. With 20 mL of 1 mol/L HCl solutions applied to the SCWO-treated waste printed circuit boards, the electrokinetic process used an electric field. Metal ions or ionic complexes were formed and migrated to the cathode or anode, respectively. The supercritical water oxidation method was found to be efficient enough to decompose the organic compounds of waste printed circuit boards, with XRD spectra suggesting that copper and lead were oxidized to CuO, Cu_2O, and PbO_2.

Vacuum Metallurgical Technology

Since there is no wastewater contamination, vacuum metallurgical technology has been used to extract metals from WEEE in recent years. The difference in vapor pressure of these metal elements at the same temperature is used to distinguish metals (as shown in Fig. 3.9). A number of waste printed circuit boards can effectively insulate and recycle various metals by means of a separation test. Heat transfer, evaporation, mass transfer, and condensation are critical processes in metals vacuum distillation.

Zhan and Xu [84], Zhan and Xu [85], Zhan and Xu [86], Zhan and Xu [87] performed a series of studies using a self-made vacuum furnace to recycle metals from waste printed circuit boards (as shown in Fig. 3.9). The findings show that Cd can be preferentially evaporated, allowing Zn to be isolated due to their large vapor pressure gaps. The evaporation process is hindered by a directly sublimated surface oxidation movie and mixed metal particles of Zn and Cd. The low-vapor pressures developed by Pb-Bi alloy makes it harder to separate Pb. Due to a type of Pb–Sn alloy, Pb was also found in the solders of waste PCBs.

Fig. 3.9 Illustration of the vacuum recovery system for distillation [28]

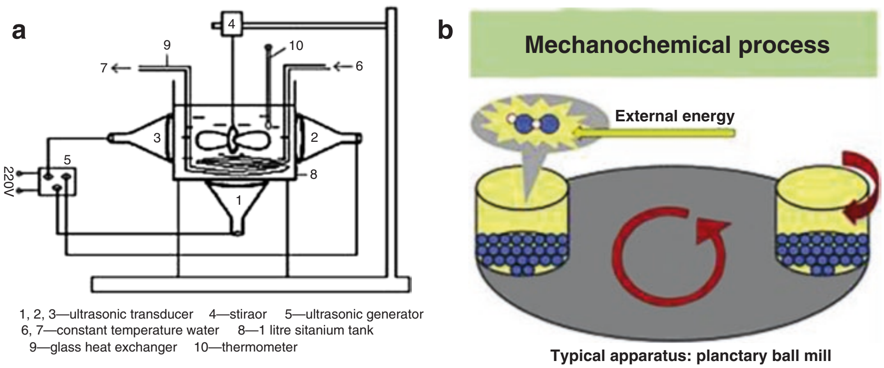

Fig. 3.10 (**a**) ultrasonically assisted leaching technology; (**b**) mechanochemical technology [28]

Ultrasound Technology

Ultrasound technology was used in the recycling of metals. Using ultrasonically aided acid leaching, recover copper and iron from waste printed circuit boards sludge. Figure 3.10 depicts the ultrasonically assisted leaching experiment unit. First, the sample was pre-treated by pouring the sample in a beaker with water and a percentage of 30 hydrogen peroxide (H_2O_2) while stirring at 300 rpm for 60 min at room temperature (25 °C). The slurry was then filtered after applying lime to the sample. The pH of the solution was cut down to less than 1.5. The results indicate that copper can essentially be isolated from iron with a production of copper and iron of respectively 93.76% and 2.07%, with an improvement of energy from ultrasounds [88, 89].

Mechanochemical Technology

The mechanochemical process can make the recycling of certain wastes (such as CRTs funnel glass, technically feasible). Tan and Li summarized [90] a systematic analysis of the utilization of mechanochemistry in metal recycling wastes, applying mechanochemical techniques to investigate the modification on the physicochemical properties, reactions, and mechanisms that can take place throughout these processes (as shown in Fig. 3.11). Pre-treatment can be achieved with mechanochemical technology, and then metals can be recycled with hydrometallurgical technology. The metal recovery rate was significantly higher in this method than in conventional hydrometallurgy. A report on the approaches used for the recycling of metals from E-waste is presented in Table 3.13 [66, 90, 92, 93].

3.3.3.3 Recycling and Recovering of Plastic

Plastics are considered the second largest component by weight, corresponding to approximately 21% of the e-waste. PS and ABS, as well as PP, account for the majority of plastics in mixed electronics waste. According to the experience of a plastics manufacturing company, these products make up about 55% of the input content, with the remaining 40–50% consisting of uneconomically recoverable plastic, flame retarded materials, and impurities.

3.3.3.3.1 Mechanical Recycling: Plastic Sorting And Re-manufacturing

Before the restoration process, the mixed plastics waste that is collected all through the processing of WEEE, shredding, and dismantling shall be sorted [94, 95]. The sorting of WEEP is normally performed by utilizing what is known as a “flotation method” (also known as “sink and float”). This method allows the separation of polymers based on their density. In order to extract the residual impurities from polymers and to further diminish and lower their bulk, the sorting process requires the initial stages of washing and granulation; this demands diverse density baths in big tanks, with dissimilar flotation media (such as pure water or water added with salts or other substances) to alter the threshold density at the anticipated value [96].

Mostly PP (which accounts for around 24% of the total e-waste containing plastics) but also a small quantity of PE (0.79%), can be simply isolated, possess a density of less than 1.0 kg/L, and are sent to plastic restoration alongside the ABS and PS (including HIPS), which can have some bromine content of concentration levels less than 2000 mg/L and a density of 1.0–1.1 kg/L [97]. Some particle-filled and fiber-reinforced styrene and polyolefins. This substantial fraction, along with other sorting residues, including fines, dust, sludge, and unrecyclable light

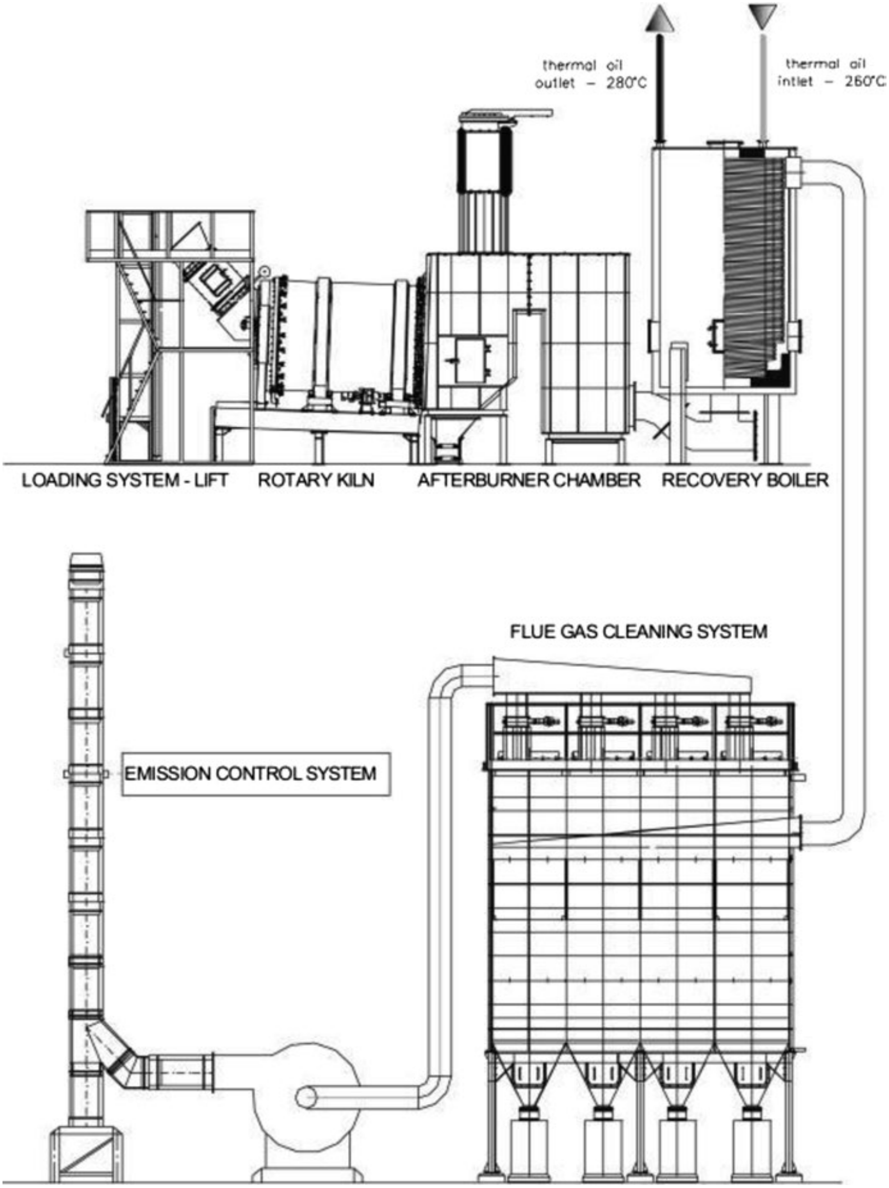

Fig. 3.11 Waste recycling system with heat recovery [91]

polymers, is discarded in landfills or incinerated in incineration facilities. This means that two critical WEEP fractions, PC (2.72% of total) and PC + ABS (5.14%), cannot be restored.

Table 3.13 Report on the approaches used for the recycling of metals from E-waste [66, 90, 92, 93]

Recycling technology	State of recovery metals	Species and effect of recovery metals	Advantages of the environmental and technological aspect	Disadvantages of the environmental and technological aspect
Electrochemical technology	Pure solid metals	Only for specific metals; fast rate of recovery	High productivity in recovery; low investment costs; mature technologies	Pollution of wastewater and residues; limited industrialization
Vacuum metallurgical technology	Solid single metal	For high vapor metals only; a high rate of recovery	Environmentally friendly; short process technology	Relatively high investment costs; poor industrialization
Biometallurgical technology	Solution	Only for a few metals specific; significant rate of recovery for Cu, Zn, Au, etc.	Pleasant to the environment; low investment costs	High metal selectivity (only for a few particular metals such as Cu, Zn, Au)
Supercritical technology	A solid mixture of metals	Almost any metal; high rate of recovery	Performance in recovery; low investment costs; low environmental impact	Recycling failure of single metal; emissions of waste oil and waste gas; low industrialization
Pyrometallurgical technology	Pure solid metals	Almost any metal; high rate of recovery	Fully commercial; due to a dust chamber and exhaust gas processing plant	High investment costs; fine particulate pollution; oil consumption; hard to recover precious metals
Mild extracting technology	Solution	Nearly all metals; reactive recovery time and reaction conditions	Low toxicity, quick and convenient accessibility, relatively low pollution	High costs for certain reagents; such reagents can lead to wastewater pollution
Other metallurgical technologies (ultrasonically, mechanochemical technology, etc.)	A solid mixture of metals/ solution	Need to recycle metals in combination with other technology	Friendly for the environment; low investment costs	Recycling of single metal; no industrialization

Thermal Treatment

The combustion process is used mostly for WEEPs with efficient mechanical recycling processes, which provide a high quality of recycled polymers. Gasification and pyrolysis are two alternatives to combustion that are not widely used [98] and therefore have not been considered.

Loading System

The plastic waste generated during processing is carried via a loading system to the incinerator facility. Waste in the recycling plant is shredded and compressed. After that, the waste in its form is inserted and applied into large containers, with a volume of 370 or 770 L. The computer device weighs and records the container and its contents automatically. The elevator then raises it above the loading chamber and empties it fully. When the loading chamber is completed, the waste is pushed into the rotary kiln by a horizontal hydraulic cylinder. The average loading frequency is every 15 min, with an average load weight of 50 kg.

Rotary Kiln

Rotative kiln built with a tilt of 2% to the side combustion chamber (afterburner), where plastic waste is incinerated. The duration and the volume of moisture of the waste are calculated by the LCV and by the amount of water content in the waste. Due to the waste's high LCV, a combustion chamber with a wide diameter in comparison to its length is commonly employed (diameter of 2 m and length of 4 m).

Secondary Combustion (Afterburner) Chamber

After the combustion process, the gases are emitted during the rotary kiln's incineration process. The procedure is performed at high temperatures ranging from 1100 to 1200 °C, with a minimum retention time of 2 s for incinerated gases.

Recovery Boiler

The generated flue gas at high temperatures (1100–1200 °C) heats up the produced thermal oil to a temperature of about 280 °C after exiting the reactor. The thermal oil is provided to processing equipment through special pumps. Finally, the generated flue gases are cooled down to lower temperatures (265 and 280 °C) as they pass through the heat recovery system.

Flue Gas Cleaning System

Multisectional bag filter is to extract dust from flue gas cleaning device. This system also includes sorbent and urea dosing metering units.

3.3.3.3.2 Landfill

The reason plastics waste is sent to the landfill is that plastics take centuries time to degrade. A landfill is the most cost-effective and transparent WEEP option. Landfilling of plastic waste is widely accepted and applied in both developed and developing countries. Usually, in developed countries and some developing countries, the landfill is engineered in a sustainable way, where it can capture the generated biogas. Further, a liner system is also employed to avoid soil and water pollution.

Throughout the process of a landfill, and with time, the release of some hazardous substances (i.e., brominated flame retardants (BFRs)) is imminent. Nevertheless, the collected leachate can be sent to wastewater treatment plants (WWTP) facility, which is usually located in the vicinity of the landfill [99]. Meanwhile, landfilling can also release other air emissions, such as greenhouse gases, which include fossil, CO_2, and CH_4. These emissions can be measured using a 3% carbon degradation rate, an average biogas composition (55% CH_4 and 45% CO_2), and a 55% biogas collection quality. The associated emissions have been estimated based on the analysis by [100]. Biogas is presumed to be transferred to a "combined heat and power (CHP) system" for energy recovery and for the reduction of greenhouse gases.

3.4 Conclusion

The various definition has been given to WEEE, and it is very important to have it updated timely with the technology advancement. Generally, WEEE can be defined as any unused electric/electronic part that has the prospect to be reused in any manner. Nonetheless, the classification of WEEE is considerably important, particularly in relation to the recycling process and the type of materials. More research should be urged in order to develop a higher efficiency of recycling processes. Policies establishment plays a very important part in each stage from the development, production, trading, and disposing of an EEE product. In the development or designing stage, the establishment of policy such as RoHS, as examples, enforces the technology developers to utilize safer materials in their product and production process. The execution of the policies that have been established is the crucial factor in achieving the objectives; thus, enforcement of the law and regulations is the key to a prolific policy. Improper WEEE management leads to a devastating effect on nature. The adverse effects of improper WEEE management include contamination of soil, air, water and climate change, which directly affect human life. Thus, managing WEEE should be a collective effort from the producer, the user, and the policymaker. The readers are referred to the literature for additional information on disposal and management of WEEE [101–103].

Glossary

Biometallurgy It refers to the biotech processes that involve the exchanges between microorganisms and metals or metal-bearing minerals.

Commingled Recycling This means a scheme where waste is mixed in a recycling truck rather than separated into individual commodities by the depositor. These materials are later sorted out at a Materials Recovery Facility (MRF).

Conventions An arrangement between states covering specific issues, especially one less formal than a treaty.

Device Stockpiling Is the end-user mentality to store their old EEE.

EEE Electrical and electronic equipment.

End of Life Is the end of a product life cycle which impedes updates for users that indicate that the product is at the end of its utility life or obsolete product life.

Greenhouse Gases Infrared gases that absorb and emit radiation within the earth's wavelength range.

Hydrometallurgy Involves the use of aqueous chemistry for the recovery of metals from ores, concentrates, and recycled or residual materials.

Informal Recycling Is an improper recycling process with no proper safety measure for the manpower and the environment.

Landfill A process of disposing of solid waste in a way that preserves public health and the environment. Every day the waste is compacted and covered. The waste disposal is screened down and the liquid and gas collected, and gate control and weighbridge is mounted.

Municipal Waste Is the solid waste material commonly called "trash" or "garbage" that is generated by homeowners and businesses

Pyrometallurgy Extraction and purification of metals by processes involving the application of heat.

Recycling Is the process of converting waste materials into new materials and objects.

RoHS Directive Is a directive to reduce or eliminate the content of the hazardous substance in the production of EEE.

Stakeholder Individual or institution (public and private) interested and involved in related processes and activities associated with a modernization process, plan, project goal, or desired change.

Urban Mining Can be defined as the "process of recovering rare metals through mechanical and chemical treatments from urban mine which is a stockpile of rare metals in the discarded WEEE of a society."

WEEE Waste for electric and electronic equipment or equipment that are no longer functional.

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Chapter 4
Health-Care Waste Management

Hamidi Abdul Aziz, Fatehah Mohd Omar, Herni Abdul Halim, and Yung-Tse Hung

Abstract Health-care waste (HCW) is the term used to describe all waste generated by health-care facilities, laboratories, and research facilities. HCW is largely non-hazardous, with an 85% recycling rate comparable to household waste. The remaining 15% is considered a hazardous material, which can be infectious, chemical, or radioactive. Measures to ensure safe and environmentally sound management of HCW must be implemented to avoid the release of chemical or biological hazards, including drug-resistant microorganisms that could harm patients and health-care workers and the general public. When HCW is not properly handled and disposed of, there is a serious risk of secondary disease transmission to waste pickers, waste workers, health-care workers, patients, and the community as a whole. Sources, generation, compositions, and risk factors for HCW are addressed in this chapter. Discussions on appropriate treatment technologies and their applications in selected countries follow the introduction of the concept of 3R's (reduce, reuse, recycle). HCW management's legal framework, regulations, and code of conduct are also highlighted. At the end of the chapter, the Covid-19 pandemic's effects on HCW management are also discussed.

Keywords Health-care waste · Composition · Waste hierarchy · Incinerator · Covid-19

H. A. Aziz (✉)
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Solid Waste Management Cluster, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: cehamidi@usm.my

F. M. Omar · H. A. Halim
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: cefatehah@usm.my; ceherni@usm.my

Y.-T. Hung
Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, OH, USA
e-mail: y.hung@csuohio.edu

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Abbreviations

BEP	Best environmental practices
CBMWTF	Common biomedical waste treatment facilities
CW	Clinical waste
EU	European Union
HCW	Health-care waste
HCWGR	Health-care waste generation rates
HDPE	High density polyethylene
LDPE	Low density polyethylene
PETE	Polyethylene terephthalate
PP	Polypropylene
PVC	Polyvinyl chloride
RMW	Regulated medical waste
US EPA	United States Environmental Protection Agency
WHO	World Health Organization

4.1 Introduction

Health-care waste (HCW) is defined as any solid waste generated during human diagnosis, treatment, or immunisation processes. HCW waste includes items such as wipes, gloves, paper towels, syringes, needles, bandages, or dressings containing small amounts of dry blood or fluid, and any other medical waste. Health-care waste is generated by a variety of health-care facilities, private offices, home health-care, clinical laboratories, and research laboratories. The safe management of HCW is seen as a challenge due to its vast volume of production, substantial negative health and environmental effects, and high disposal costs. The generation of HCW has rapidly expanded as the number of health-care facilities and advanced medication in health-care centres has increased. Throughout the world, numerous research is being conducted to define good practice guidelines and provide the best options for proper HCW disposal with the least amount of risk to human health and the environment. Although substantial progress has been made, more has to be done to reduce infectious dangers and contamination of the environment. Despite the severe health dangers and potential environmental damage, HCW management has received little attention in poor countries. A comprehensive waste management plan requires knowledge of the sources of HCW generation and how these wastes are addressed at the source. A proper HCW management requires proper focus on the followings (1) generation and minimisation; (2) source separation and segregation; (3) identification and labelling; (4) handling and storage; (5) safe transportation; (6) treatment; (7) residue disposal; (8) occupational safety and health; (9) public and environmental health; (10) research and development into improved technologies and environmentally friendly practices. It is also necessary to have appropriate guidelines for securely disposing of HCW under local conditions in each country.

4.2 Definition and Classification of Health-Care Waste (HCW)

4.2.1 Terminology

In broad terms, HCW can be classified into the following categories:

1. Solid waste from non-sharp items contaminated with human fluids or biological material which may include clothes, gloves, pipettes, or tissue culture.
2. Liquid waste which includes large amounts of blood or body fluids.
3. Sharps waste includes any material that can puncture or penetrate the skin and is tainted with biological material that could spread or be released into the environment. Examples include scalpels, needles, syringes, broken glass, microscopic slides, and tubes.
4. Medical waste, known by a variety of names, all of which have the same basic description, i.e. the type of waste that is infected or possibly contaminated by infectious material and is generated throughout the health-care procedure.

All of them alluded to the waste generated by medical procedures in health-care facilities, research centres, and laboratories. It also includes the same types of waste that come from minor and dispersed sources, such as garbage produced during in-home health-care (such as self-administration of insulin, home dialysis, and recuperative care). Although the phrases are sometimes interchanged, there is a difference between ordinary HCW and hazardous medical waste. The WHO classifies human tissue, fluids, sharps, and contaminated supplies as “biohazardous”, while non-contaminated appliances and animal tissue are classified as “generic medical waste”. Medical waste also includes office paper, general garbage, and cooking waste from health-care facilities, even though it is not regulated and is not harmful in nature.

There are also other definitions which include hospital waste, health-care waste, medical waste, biomedical waste, biohazardous waste, clinical waste, Regulated Medical Waste (RMW), and infectious medical waste. However, health-care waste (HCW) will be used in this chapter. There is a need for a uniform and internationally accepted definition of waste created in health-care amenities to get a better understanding of waste management in those facilities. World Health Organisation (WHO) [1] has defined these as detailed in Fig. 4.1.

4.3 Sources and Generation of HCW

4.3.1 Sources

There are guidelines that are applicable for HCW generated from health-care establishments, which can be grouped as follows (Table 4.1).

Fig. 4.1 Classification of HCW [1]

Table 4.1 Types of health-care establishments that generate waste

Large source	Medium source	Small source
• University hospitals and clinics	• Medical centres	• General medical practitioners
• Maternity hospitals and clinics	• Outpatient clinics	• Convalescent homes
• General hospitals	• Mortuary/autopsy facilities	• Nursing homes for the elderly
• District hospitals	• Farm and equine centres	• Medical consulting rooms
	• Hospices	• Dental practitioners
	• Medical laboratories	• Animal boarding
	• Medical research facilities	• Acupuncturist
	• Animal hospitals	• Veterinary practitioners and animal research
	• Blood banks and transfusion centres	• Pharmacies
	• Emergency services	• Cosmetic piercers
	• Obstetric and maternity clinics	• Mortuary and autopsy centres
	• Outpatient clinics	
	• Dialysis centres	
	• Military medical services	

Fig. 4.2 Category of HCW [1, 2]

According to WHO [1, 2], about 85% of the total waste created by health-care activities is ordinary, non-hazardous waste. The remaining 15% is classified as hazardous waste, as shown in Fig. 4.2.

Around the world, approximately 16 billion injections are given each year. Unfortunately, quite a significant amount of needles and syringes are not properly managed. Dioxins, furans, and particulate matter may be produced from open burning and improper incineration of medical waste. It is important to make sure that HCW is handled in a safe and environmentally sound manner so that it does not pose a risk to patients, health-care staff, and members of the general public, all of whom could be exposed to potentially harmful chemicals or microorganisms [2].

4.3.2 Generation of HCW

Several surveys have revealed the usual generation of HCWs. WHO [3] has reported statistics from various research works by different workers on the quantity of waste produced by health-care sources. Table 4.2 shows the data for Pakistan, Tanzania, and South Africa. Data for the United States of America is shown in Table 4.3.

Minoglou et al. [4] has summarised the HCW generation rates in selected countries based on various studies conducted in the world (Table 4.4). The waste generation rates by type of facility are further detailed in Table 4.5 [1]. Recent data of HCW generation rates are given in Fig. 4.3.

4.3.3 Compositions of HCW

WHO [5] has summarised from different sources various data on HCW compositions. These are shown in Tables 4.6, 4.7, 4.8, and 4.9. When establishing recycling programmes, it is critical to determine the material composition of general garbage.

Table 4.2 Different waste categories generated by health-care facilities in Pakistan, Tanzania, and South Africa [3]

Type of health-care facility	Total health-care waste generation	Infectious waste generation
Pakistan		
Hospitals	2.07 kg/bed/day (range: 1.28–3.47)	
Clinics and dispensaries	0.075 kg/patient-day	0.06 kg/patient-day
Basic health units	0.04 kg/patient-day	0.03 kg/patient-day
Consulting clinics	0.025 kg/patient-day	0.002 kg/patient-day
Nursing homes	0.3 kg/patient-day	
Maternity homes	4.1 kg/patient-day	2.9 kg/patient-day
Tanzania		
Hospitals	0.14 kg/patient-day	0.08 kg/patient-day
Health centres (urban)	0.01 kg/patient-day	0.007 kg/patient-day
Rural dispensaries	0.04 kg/patient-day	0.02 kg/patient-day
Urban dispensaries	0.02 kg/patient-day	0.01 kg/patient-day
South Africa		
National central hospital		1.24 kg/patient-bed/day
Provincial tertiary hospital		1.53 kg/patient-bed/day
Regional hospital		1.05 kg/patient-bed/day
District hospital		0.65 kg/patient-bed/day
Specialised hospital		0.17 kg/patient-bed/day
Public clinic		0.008 kg/patient-day
Public community health centre		0.024 kg/patient-day
Private day-surgery clinic		0.39 kg/patient-day
Private community health centre		0.07 kg/patient-day

Table 4.3 Total and infectious waste generation in a high-income country (United States of America), [3]

Type of health-care facility	Total health-care waste generation	Infectious waste generation
Metropolitan general hospitals	10.7 kg/occupied bed/day	2.79 kg/occupied bed/day
Rural general hospitals	6.40 kg/occupied bed/day	2.03 kg/occupied bed/day
Psychiatric and other hospitals	1.83 kg/occupied bed/day	0.043 kg/occupied bed/day
Nursing homes	0.90 kg/occupied bed/day	0.038 kg/occupied bed/day
Laboratories	7.7 kg/day	1.9 kg/day
Doctor's office (group practice, urban)	1.78 kg/physician-day	0.67 kg/physician-day
Doctor's office (individual, urban)	1.98 kg/physician-day	0.23 kg/physician-day

(continued)

Table 4.3 (continued)

Type of health-care facility	Total health-care waste generation	Infectious waste generation
Doctor's office (rural)	0.93 kg/physician-day	0.077 kg/physician-day
Dentist's office (group practice)	1.75 kg/dentist-day	0.13 kg/dentist-day
Dentist's office (individual)	1.10 kg/dentist-day	0.13 kg/dentist-day
Dentist's office (rural)	1.69 kg/dentist-day	0.13 kg/dentist-day
Veterinarian (group practice, metropolitan)	4.5 kg/veterinarian-day	0.66 kg/veterinarian-day
Veterinarian (individual, metropolitan)	0.65 kg/veterinarian-day	0.097 kg/veterinarian-day
Veterinarian (rural)	7.7 kg/veterinarian-day	1.9 kg/veterinarian-day

Table 4.4 Health-care waste generation rates (HCWGR) in selected countries [4]

	Country	HCWGR (kg/bed/day)	Country	HCWGR (kg/bed/day)
Africa	Algeria	0.96	Mauritius	0.44
	Cameroon	0.55	Morocco	0.53
	Egypt	1.03	Sudan	0.87
	Ethiopia	1.1	Tanzania	0.75
Asia	Bangladesh	1.24	Malaysia	1.9
	China	4.03	Pakistan	2.07
	India	1.55	Palestine	2.02
	Indonesia	0.75	Thailand	2.05
	Iran	3.04	Turkey	4.55
	Japan	2.15	Nepal	0.5
	Jordan	2.69	Lebanon	5.7
	Korea	2.4	Kazakhstan	5.34
	Laos	0.51	Vietnam	1.57
America	Argentina	3	Ecuador	2.09
	Brazil	2.94	El Salvador	1.85
	Canada	8.2	USA	8.4
Europe	Bulgaria	2	Netherlands	1.7
	Italy	4	Norway	3.9
	France	3.3	Spain	4.4
	Germany	3.6	Latvia	1.18
	Greece	3.6	UK	3.3

Table 4.5 The waste generation rates by type of facility. Adapted from [1]

Facility	Total HCW generation rate	Infectious HCW generation rate
Hospital	2 kg/bed-day	0.5 kg/bed-day
Clinic	0.02 kg/patient-day	0.007 kg/patient-day
Clinical laboratory	0.06 kg/test-day	0.02 kg/test-day
Maternity Centre	5 kg/patient-day	3 kg/patient-day
Basic Health Unit	0.04 kg/patient-day	0.01 kg/patient-day

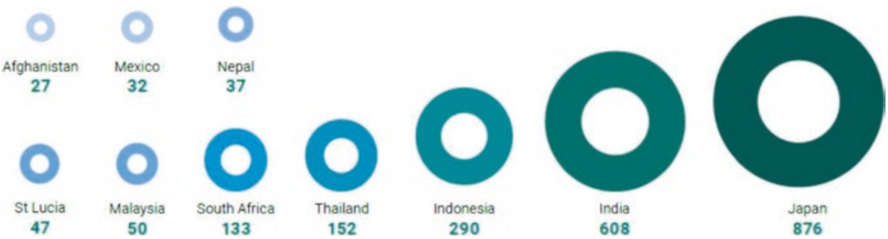

Fig. 4.3 HCW generation rates in selected countries (tonnes/day) [1]

Table 4.6 Bulk densities of HCW by components [5]

Canada		Ecuador	
Component	kg/m^3	Component	kg/m^3
Human anatomical	800–1200	General wastes	596
Plastics	80–2300	Kitchen wastes	322
Swabs, absorbents	80–1000	Yard wastes	126
Alcohol, disinfectants	800–1000	Paper/cardboard	65
Animal infected anatomical	50–1300	Plastic/rubber	85
Glass	2800–3600	Textiles	120
Bedding, shavings, paper, faecal matter	320–730	Sharps	429
Gauze, pads, swabs, garments, paper, cellulose	80–1000	Food wastes	580
Plastics, polyvinyl chloride (PVC), syringes	80–2300	Medicines	959
Sharps, needles	7200–8000		
Fluid, residuals	990–1010		

The heating value for incineration would be influenced by the moisture level of various components of overall HCW.

Hospital waste contains around 37% carbon, 18% oxygen, and 4.6% hydrogen, together with a variety of other components (Liberti et al. [6]). Mercury, lead, cadmium, chromium, arsenic, and zinc are among the hazardous elements contained in HCW and easily discharged during combustion (WHO [5]).

UNDP [7] has provided data on HCW waste in general. In most hospitals, the total waste created per bed per day is between 2 and 4 kg. Infectious waste created per bed per day in hospitals with effective separation is roughly 0.2–0.4 kg. Healthcare waste has an average bulk density of 100–200 kg/m^3. In 2020, WHO [1] had revealed fresh data on the compositions of HCW (Table 4.10).

Table 4.7 Average composition of HCW WHO [5]

Jordan		Peru		Turkey		Taiwan (China)		Kuwait		Italy	
Component	%	Component	%	Component	%	Component	%	Component	%	Component	%
Paper	38	Mixed paper	22	Paper	16	Paper	34	Paper	24	Paper	34
		Cardboard	5	Cardboard	5			Cardboard	8		
Plastic	27	Plastic	12	Plastic	41	Plastic	26	Plastic	18	Plastic	46
Glass	10	Glass	8	Glass	7	Glass	7	Glass	10	Glass	8
Metals	5			Metal	2	Metal	4	Metal	9	Metal	0.4
				Food	17	Food	15	Food	12		
Textiles	11	Cotton/gauze	18	Textiles	10	Textiles	9	Textiles	11		
		Placenta	8							Anatomical	0.1
Garbage	9	Other	27	Other	3	Other	3	Other	8	Liquids	12

Table 4.8 Moisture content (%) of HCW components [5]

Overall HCW (%)					Infectious waste (%)	
Component	Ecuador	Component	Jordan	Turkey	Component	Canada
Paper/cardboard	16	Paper	22–57	4.5	Human anatomical	70–90
Food	45	Food		63	Plastics	0–1
Textile	30	Textile	37–68	8.6	Swabs, absorbents	0–30
Plastic/rubber	15	Plastic	11–54	2.8	Alcohol, disinfectants	0–0.2
Kitchen waste	47	Garbage	37–57		Animal infected anatomical	60–90
Garden Wastes	40	Carton		5	Glass	0
Medicines	64	Metal		2.25	Bedding, shavings, paper, faecal matter	10–50
		Glass		2.05	Gauze, pads, swabs, garments, paper, cellulose	0–30
		Other		8	Plastics, polyvinyl chloride, syringes	0–1
					Sharps, needles	0–1
					Fluid, residuals	80–100

Table 4.9 Heating value of health-care waste components. Adapted from WHO [5]

Component	Heating value (as fired)	
	MJ/kg	kcal/kg
Human anatomical	2–8.4	400–2000
Plastics	32–46	7700–11,000
Swabs, absorbents	13–28	3100–6700
Alcohol, disinfectants	25–32	6100–7800
Animal infected anatomical	2–15	500–3600
Glass	0	0
Bedding, shavings, paper, faecal matter	9–19	2200–4500
Gauze, pads, swabs, garments, paper, cellulose	13–28	3100–6700
Sharps, needles	0–0.1	0–30
Fluids, residuals	0–5	0–1100

Table 4.10 Common compositions of HCW [1]

Name of the country/city	Composition of HCW (%)	
	Hazardous	Non-hazardous
National level		
India	10–25	75–90
Kenya	15	85
Malaysia	20	80
Nepal	27	73
City level		
Dhaka city (Bangladesh)	18	82
Surabaya (Indonesia)	27	73
Pangkal Pinang (Indonesia)	10–30	70–90
Padang (Indonesia)	20	80

4.3.4 Dangers and Risks of HCW

HCW contains a significant amount of ordinary garbage and a small amount of hazardous waste. This section discusses the dangers of being exposed to hazardous (or risky) HCW. Health-care employees, trash workers, and the general public may be exposed to HCW if it is not properly regulated. For example, if needles are accidentally delivered to recycling facilities and their containers break open, they could pose a danger of infection. Housekeepers, housekeepers, janitors, and rubbish collectors are all at risk because sharps might protrude from plastic bags. Toxic waste contains bacteria, radioactive damage to the skin and respiratory system, poisoning, and environmental contamination. Our drinking water and the ecology could also be harmed by poorly discarded rubbish in landfills.

There are common health hazards known to be associated with HCW. These hazards can endanger the community in three modes: (1) as a result of accidental exposure to rubbish at municipal waste disposal facilities; (2) by exposure to chemical or biological pollutants in water, and (3) through exposure to chemical contaminants (e.g. mercury) from waste incineration.

4.3.4.1 Types of Hazards

Disease or harm can occur due to exposure to hazardous HCW. Figure 4.4 shows how the harmful nature of HCW may be linked to its features.

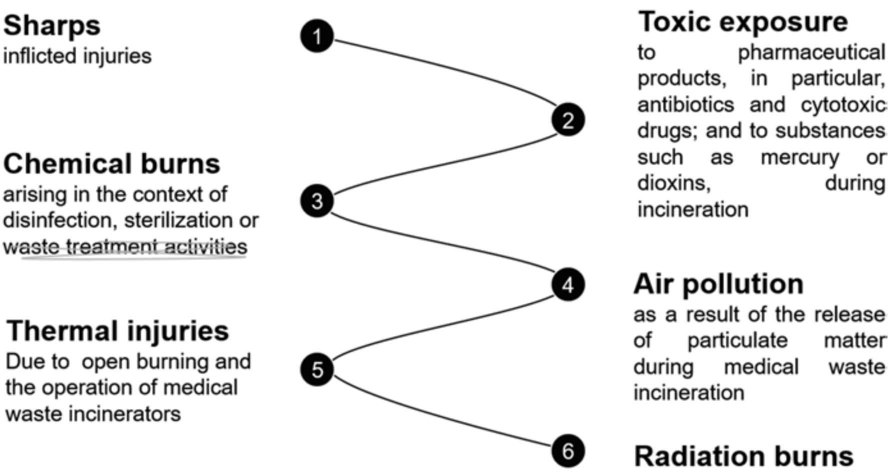

Fig. 4.4 The most common hazardous nature of HCW World Health Organisation [8]

4.3.4.2 Affected Individuals

Individuals who are exposed to hazardous HCW, as well as those who work in health-care facilities that produce hazardous waste and those who work outside of these facilities which are exposed to hazardous waste as a result of poor management, are all at risk. Figure 4.5 depicts the primary groups at risk.

The dangers of scattered, minor sources of HCW cannot be disregarded. Home HCW, such as dialysis waste and illicit drug use (usually intravenous) waste, are two examples of this type of waste.

4.3.4.3 Hazards by Infectious Waste and Sharps

A wide range of harmful bacteria can be found in infectious waste. Waste pathogens reach the human body in a variety of ways:

1. via a puncture, abrasion, or cut in the skin
2. via mucous membranes
3. via inhalation
4. via uptake

Sharps are classified as a particularly hazardous waste class because of the twofold risk of harm and disease transmission. Hypodermic needles are a major component of the sharps waste category, and they are particularly dangerous because they are frequently contaminated with blood from patients. Polluted sharps (especially

Fig. 4.5 The main risk group in HCW management

hypodermic needles) and concentrated pathogen cultures are among the waste products that pose the greatest danger to one's health. Sharps can cause more than just cuts and punctures; if they are tainted with microorganisms, they can also infect the wounds.

4.3.4.4 Pharmaceutical and Chemical Waste Hazards

Pharmaceutical wastes, like many substances, can be harmful. They can be highly flammable, caustic, or explosive. A health-care facility's pharmaceutical waste might come from a variety of activities and places. Expiring, underused, and possibly tainted pharmaceuticals, such as vaccinations and biological materials used for therapy, gloves, masks, and bottles, are all included in this type of garbage. Pharmaceutical waste presents a unique treatment and management problem. Large volumes held at pharmacies, distribution facilities, hospitals, and other locations must be controlled to minimise the risk of leakage or public exposure. As well as being harmful to patients and the environment, certain drugs are genotoxic (cause cancer in humans) or mutagenic (damage genetic material). Carcinogenic and/or teratogenic waste is produced by medical facilities that treat cancer.

Many chemicals and medications used in health-care are dangerous (WHO [5]). They are typically discovered in small amounts in HCW, but larger amounts can be detected when undesired or outmoded chemicals and medications are discarded. Chemical wastes can cause intoxication through acute or chronic exposure, as well as physical damage such as chemical burns, which are the most prevalent. Intoxication can occur when a chemical or medicine is absorbed through the skin or mucous membranes or when it is inhaled or consumed. Skin, eyes, and mucous membranes of the airways may be damaged by flammable or caustic chemicals that come into contact with the skin, eyes, or airways (e.g. formaldehyde and other volatile substances). Laboratory workers, particularly in speciality and research hospitals, are exposed to dozens of chemicals on a daily basis.

The hazardous qualities that are most important to HCW, as listed by WHO in 2014 [5]. The following is included:

- Toxic. At some amount of exposure, most substances are hazardous. Toxic fumes, dust, and vapours are especially dangerous because they can be breathed and swiftly move from the lungs into the bloodstream, allowing for fast circulation throughout the body.
- Corrosive. Strong acids and alkali bases can erode other materials, which include clothing, totally. They can inflict significant chemical burns and irreversible harm if splashed on the skin or eyes. Some of them also decompose into deadly gases, making them much more dangerous.
- Explosive. When exposed to heat or flame, some materials, such as volatile liquids, are ignited in small spaces, and the uncontrolled release of pressurised gases can explode.

- Flammable. Some compounds can easily cause a fire in a substance. Burn quickly, spread quickly, and emit a lot of heat. Solvents, fuels, and lubricants are among the flammable compounds kept in laboratories, medical areas, and workshops.
- Reactive chemically. Proper containers should be used when handling these compounds. When exposed to air or water, some can burn, while others can burn when mixed with other chemicals. It is worth noting that reactive materials can burn without being exposed to heat or flames. Any time they come into contact with air, they have the potential to spontaneously catch fire and release hazardous fumes.

4.3.4.5 Genotoxic Waste Hazards

Because it can cause mutation, teratogenicity, or carcinogenesis, genotoxic waste is particularly hazardous. It raises serious questions about patient safety, both during treatment and afterwards, and as a result, it should be handled with utmost caution. Genotoxic waste includes the following: cytostatic drugs, vomit, urine, or faeces from people who have undergone cytostatic treatment, chemicals, and radioactive substances.

The main compounds in this category, cytotoxic (or antineoplastic) medicines, have the power to destroy or inhibit the growth of specific living cells and are employed in cancer chemotherapy. They are crucial in the treatment of a variety of cancers, but they also have a wide range of applications as immunosuppressive drugs in organ transplantation and the treatment of a variety of disorders with an immunological base. In oncology and radiotherapy units, cytotoxic drugs are most widely used; however, their usage in other medical departments is increasing, and they may also be used outside of the hospital setting. The most commonly used genotoxic substances in medical practice are (1) chemicals (benzene), (2) radioactive materials, and (3) other cytotoxic and other drugs (azathioprine, chlorambucil and chlornaphazine, cyclosporin, cyclophosphamide and semustine, tamoxifen, thiotepa, treosulfan).

Many antineoplastic medications have been proven to be carcinogenic and mutagenic in animal tests, and secondary neoplasia (developing after primary cancer has been eliminated) has been linked to some types of chemotherapy (WHO [5]).

Many cytotoxic medications are extremely irritating and can cause serious local side effects when they come into contact with the skin or eyes (Table 4.11). Dizziness, nausea, headaches, and rashes are all possible side effects of cytotoxic medicines. Any release of genotoxic waste into the environment has the potential to be terrible for the environment.

Table 4.11 Category and types of cytotoxic drugs (WHO [5])

Category	Types
Alkylating agents	Vesicant (blistering) drugs: aclarubicin, chlormethine, cisplatin, mitomycin
	Irritant drugs: carmustine, cyclophosphamide, dacarbazine, ifosfamide, melphalan, streptozocin, thiotepa
Intercalating agents	Vesicant drugs: amsacrine, dactinomycin, daunorubicin, doxorubicin, epirubicin, pirarubicin, zorubicin
	Irritant drugs: mitoxantrone
Vinca alkaloids and derivatives	Vesicant drugs: vinblastine, vincristine, vindesine, vinorelbine
Epipodophyllotoxins	Irritant drugs: teniposide

4.3.4.6 Radioactive Waste Hazards

The category of illness caused by radioactive waste is determined by the type and extent of exposure to the radioactive material. Everything from dizziness and vomiting to more serious problems might be caused by it. When exposed to high levels of radiation, radioactive waste has the potential to damage genetic material. Handling highly active sources, such as those found in diagnostic tools (e.g. gallium sealed sources), can result in far more serious injuries, including tissue loss and the need for amputation of body parts. Extreme situations may result in death. Contamination of the external surfaces of containers, as well as the wrong mode or length of waste storage, might pose risks to low-activity radioactive waste. The most vulnerable are health-care employees, as well as workers of waste handling and cleaning who are exposed to radiation.

Radioactive materials are used in both diagnostic and therapeutic processes in health-care facilities. The majority of radiation therapy is normally done in a hospital's nuclear medicine department. Radioactive waste includes medical equipment contaminated with trace amounts of specific isotopes, clothing, biological material (pathological waste), and the radiation source itself (e.g. a cobalt block). Body parts and fluids can become radioactive when radioactive elements are injected into human bodies, such as iodine to treat a damaged thyroid gland or iridium pellets to eliminate prostate cancers. The urine and faeces of the patient may include pathological radioactive waste. By infusing radioactive antigens into the bloodstream, radioimmunoassay is a frequently used technique for determining the amounts of chemicals inside the body. Radioactive wastes could include packaging materials, cleaning fluids, and paper wipes.

Fortunately, some of the radioactive elements used in the human body have very short half-lives. Fast-decaying isotopes are chosen partially to reduce negative effects and to ensure that residual radiation does not harm healthy tissue. As a result, isotope containing waste tends to lose its radioactivity rapidly, lowering the dangers of storage and disposal. Every situation and utilisation of radioactive substances, on the other hand, must be assessed to establish the optimum storage and disposal strategy.

It takes half the atoms of each radioactive isotope to decay into a different isotope for each isotope to have its own unique half-life. One half-life produces another half-life, which can be radioactive or stable (non-radioactive), depending on the type of isotope decaying. Half-lives might be as short as a few seconds or as long as tens of millions of years.

Alpha, beta, and gamma radiation are all forms of radiation (this is oversimplified). Humans and animals can be contaminated by any of them. Using a piece of cardboard to separate the radioactive material from people is all that is needed to halt alpha and beta particles. The higher, stronger gamma rays are capable of penetrating solid materials like concrete. It is now possible to estimate the radiation dangers posed by various materials and devise protective measures.

Radiation exposure can produce headaches and nausea in the case of light exposure, as well as more significant symptoms (anaemia, skin rashes, and tissue damage) in the case of excessive exposure. Even radioactive materials employed in diagnostic tools (such as gallium) can be dangerous if they escape. Long-term exposure to radiation (if the substance remains entrenched in the body) can result in cancer and birth abnormalities in children.

Specialists can estimate how radiation levels will change over time by knowing a material's composition. The dangers caused by radioactive waste, unlike normal hazardous waste, diminish over time.

Iodine 125 has a half-life of about 60 days. Thyroid cancer patients are given iodine 131, which has an 8-day half-life and is used to destroy cancerous thyroid cells. When other isotopes are used for imaging, beta radiation is preferred since it emits the most energy.

4.4 Reduce, Reuse, and Recycling (3R's) of HCW

4.4.1 The Waste-Management Hierarchy

For public health reasons, there is a range of ways to deal with waste management. Waste hierarchy can be used as a framework for summarising the various approaches. The most desirable is at the top, while the least desirable is at the bottom (Fig. 4.6). "Desirability" is defined as the sum of the environmental, public health, financial affordability, and social acceptability implications of each method.

"Reduce, Reuse, and Recycle" (the "3Rs" concept), which broadly refers to resource sustainability, is at the heart of the waste management hierarchy's "3Rs" philosophy. It is best practice to avoid or recover as much as possible from waste at or around a health-care institution rather than burying it. It is sometimes referred to as addressing waste "at the source" rather than "end-of-pipe" solutions. Avoiding waste production as much as possible is the most optimal method if it is possible to do so. It is preferable if waste may be used for secondary purposes when possible. To decrease the health and environmental implications of waste that cannot be retrieved, the least preferred choices, such as treatment or land disposal, must still be needed.

Fig. 4.6 The waste management hierarchy

4.4.2 Waste Reduction

Over time, working with medical experts should be the goal of long-term waste reduction in the medical field (or minimisation). Waste minimisation is often employed to reduce waste at the point of generation, but health-care administrators can also reduce waste generation by modifying their purchasing and stock-control strategies. All staff should be trained in waste minimisation because they have a responsibility to discharge in this strategy. This is especially critical for employees in departments that produce substantial amounts of toxic HCW. Chemical and pharmaceutical manufacturers can play a bigger role in waste-reduction efforts. The health centre should promote this by procuring exclusively from vendors who can fulfil small orders quickly, accept returns of unopened items, and provide hazardous waste disposal services outside.

The following are some examples of policies and practices that are common to reduce waste volumes through reduction at source:

- Procurement cuts: choosing more environmentally friendly supplies and may be utilised in lesser quantities or that cause less hazardous waste.
- Physical cleaning procedures are preferred over chemical cleaning methods (e.g. steam disinfection instead of chemical disinfection).
- Product wastage can be avoided (e.g. in nursing and cleaning activities). At the hospital level, management and control procedures are in place.
- Hazardous chemical purchases are centralised.

- The use of hazardous waste chemicals in the health centre is tracked from delivery through disposal. Chemical and pharmaceutical product inventory management may also need to be implemented.
- Rather than purchasing large quantities all at once, smaller amounts should be purchased more frequently (applicable in particular to unstable products).
- A product's oldest batch should be utilised first.
- Each container's contents are fully utilised.
- Tracking the expiration dates of all items at the time of arrival and refusing to accept things from a supplier that are out of date.

4.4.3 Green Procurement

Decreased waste toxicity is also good for the environment because it makes the process of treating and disposing of it easier. A buying manager at a health-care facility, for example, could look into purchasing plastics that are easily recyclable or ordering supplies that are delivered without extra packaging.

Polypropylene, polyethylene, and polyethylene terephthalate are the most simply recyclable plastics worldwide (PET). Polyvinyl chloride (PVC), on the other hand, is the most difficult to work with, mainly because its products exist in a range of forms with various additions. Mixed-material packaging, like card or paper coated in plastic or aluminium foil, is almost never recyclable. Because of the toxicity of certain additives, PVC should be avoided wherever feasible. Bisphenol A, which is an endocrine disruptor, is also used to make polycarbonate. PVC gloves are most commonly replaced with latex or nitrile gloves. PVC tubing, polyethylene IV bags, and ethylene vinyl acetate bags for saline and blood can all be replaced by latex or silicone tubing, polyethylene IV bags, and ethylene vinyl acetate bags. Although ethylene oxide is applied to sterilise medical instruments, it is carcinogenic, and its use is highly not recommended wherever possible.

4.4.4 Reduce, Recycle, and Reuse

4.4.4.1 Recycling Symbols for Plastics

There is a worldwide categorisation system for plastics. The following are examples of common categories in health-care settings (Fig. 4.7):

Four types of polyethylene are typically used in health-care: low-density (LDPE) (4); high-density (HDPE) (5); and polypropylene (PP) or PETE (1).

Understanding the seven plastic codes will make selecting plastics and determining which plastics to recycle much easier. Water bottles with a three or a five on them, for example, cannot be recycled in most US counties. A three denotes that the water bottle is made of polyvinyl chloride, while a five indicates that it is

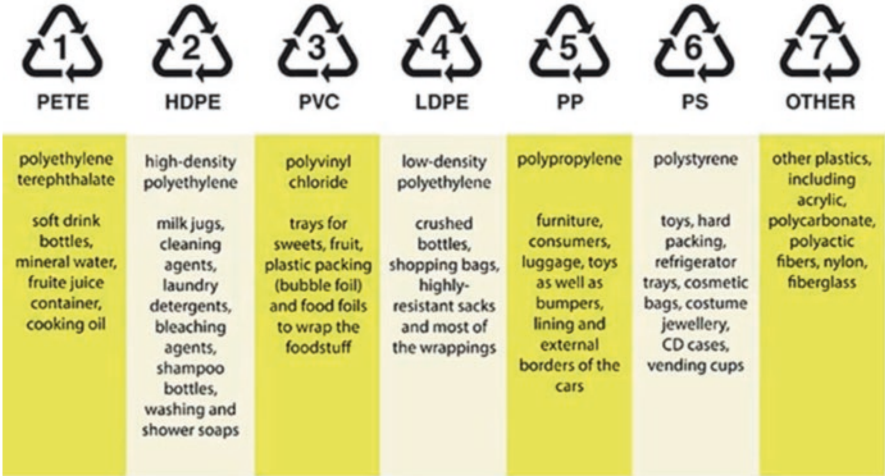

Fig. 4.7 Plastic recycling codes

constructed of polypropylene, both of which are not recognised by most public recycling centres.

4.4.4.2 Safe Reuse

Not all materials in a health-care facility can be reused, with single-use (medical) gadgets being of special concern. In general, non-disposable materials should be used for medical operations when their reuse after being washed has been proved to reduce infectious to acceptable levels. It is not acceptable to reuse single-use devices due to the unacceptable risk of cross-infection they pose.

4.4.4.3 Reuse and Recycling

Among the organisations that recycle include municipalities, commercial enterprises, homes, and public institutions like schools and hospitals. Recycling waste goods into new products and composting organic waste materials to make compost or soil conditioner for agricultural or other uses are two examples of waste recovery. “Recovery” could also apply to energy recovery, which involves converting trash into fuel for electricity generation or direct heating. On-site incinerators may be an attractive and cost-effective solution for heating hospitals, public buildings, and residential areas.

Recycling is becoming more frequent in several health-care facilities, especially for the large, non-hazardous portion of waste. Reduced disposal fees or having a recycling firm pay for waste that is recovered can reduce costs dramatically. There will be recyclable materials in some of the hazardous infectious wastes (such as cardboard, paper, packaging, tubing, etc.). The pathogens in these products can be eliminated by cleaning and adhering to safe handling guidelines.

Hospital food waste composting is also growing increasingly common, particularly in countries where landfill use is becoming more restricted due to regulation, taxes, service fees, or land constraints. But if you manage your compost properly, you can reduce the risk of attracting rodents and other pests.

In order to move current practices up the waste-minimisation hierarchy from mostly disposal to recycling or even prevention, all health-care facilities' waste-management strategies should contain the waste-minimisation hierarchy. Opportunities to reduce the amount of materials used and waste generated will be obvious at many points during the project life cycle. Educating health-care workers on how to use medical supplies responsibly is another simple option that may be implemented. It's possible to reduce waste by reusing items, but this option has its own set of challenges. As a result of the risk of infection transmission to patients and personnel, it is necessary to identify which reuse techniques are safe and which should be avoided.

In order to reduce waste, it's critical to implement life cycle management strategies for commonly used products and services. Another option is to work with suppliers to produce things made from materials that decay more quickly or maybe repurposed for secondary purposes. It is possible to reduce both physical waste and environmental impact by combining these developments in HCW waste treatment and disposal.

From an environmental, economic, and social standpoint, the waste-management hierarchy offers unambiguous recommendations on which waste-management options are most desired. These procedures should be employed if they are feasible. Minimisation is always better than generating garbage and then dealing with, treating, and disposing of it. A health-care facility should make recycling and waste reduction a part of its regular routine. All personnel should engage in waste-minimisation techniques on a daily basis to promote staff, patient, and public safety.

4.4.5 Segregation, Storage, and Transport of HCW

WHO [5] has listed concepts of waste segregation, storage, and in relation to managing the waste from its generation to disposal. Each medical area should have a separate container for each type of segregated waste; each container should be tagged when it is full so that supervisors can keep track of waste generation. It is important to classify medical waste into several categories depending on their possible hazards and disposal routes, and separate containers should be provided in each medical area to hold each of these categories of medical waste, according to the person who generates it.

As a general rule, hazardous and non-hazardous wastes should not be mixed during collection, transport, or storage; collected waste is frequently transported to a central location for treatment and disposal; staff should be aware of the risks associated with the wastes they are handling, as well as the proper disposal procedures.

The waste generator should segregate as close to the place of generation as possible. The administration of the health-care facility is responsible for ensuring that sufficient segregation, transportation, and storage system is in place, as well as that all employees follow the proper protocols. Hazardous waste should be kept separate from non-hazardous garbage. Typically, hazardous waste is divided into two categories: used sharps and potentially infectious materials. Bandages, tubing, swabs, disposable medical items, and tissues are the most common components in the latter.

Separate containers are used to separate common, non-hazardous garbage, potentially infectious waste, and used sharps. Other types of containers can be used for different sorts of trash, such as chemical and pharmaceutical wastes, or to segregate pathological waste from the rest of the waste flow, where it must be managed and disposed of differently.

A colour-coding method for trash containers is sometimes mandated by national law in a large number of nations (see, for example, Table 4.12) [9]. When waste is labelled with different colours, the potential danger that it poses can be seen more clearly.

Each region's waste containers are labelled to identify the source, track the types and quantities of waste produced in each region, and trace waste segregation concerns back to a medical area. Labelling each container with the medical area's details, the day and time it was closed, as well as a person's name is a simple

Table 4.12 Disposal method recommended by the World Health Organization [9]

Waste categories	Colour of container and markings	Type of container	Collection frequency
Infectious waste	Yellow with biohazard symbol (highly infectious waste should be additionally marked HIGHLY INFECTIOUS)	Leak-proof strong plastic bag placed in a container (bags for highly infectious waste should be capable of being autoclaved)	When three-quarters filled or at least once a day
Sharp waste	Yellow, marked SHARPS with biohazard symbol	Puncture-proof container	When filled to the line of three-quarters
Pathological waste	Yellow with biohazard symbol	Leak-proof strong plastic bag placed in a container	When three-quarters filled or at least once a day
Chemical and pharmaceutical waste	Brown labelled with appropriate hazard symbol	Plastic or rigid container	On-demand
Radioactive waste	Labelled with a radiation symbol	Lead box	On-demand
General HCW	Black	Plastic bag inside a container which is disinfected after use	When three-quarters filled or at least once a day

Fig. 4.8 Comparison of common hazardous waste symbols

approach to keep track of what's in it. Each waste container should have an international hazard emblem attached to it. Figure 4.8 illustrates a number of symbols that are relevant to the many sorts of hazardous waste that are generated in a health-care facility.

4.4.6 Collection Within the Health-Care Facility

WHO [5] also described the frequency of collection, which depends on the amount of waste generated in each section of health-care facility. Separate collection systems and collection time are normally practised for general waste, infectious or other hazardous wastes. Daily collection is normally implemented.

Ready for pickup, waste bags should be sealed. At each garbage collection point, replacement bags or containers should be accessible so that full ones may be replaced right away. Waste bags and containers should be tagged with the date, type of waste, and location of generation in order to keep track of waste from generation to disposal. It is a good idea to keep track of the waste's weight.

As part of the daily routine in a medical facility, infectious waste may be collected during the day to prevent dirty bandages from lingering in the medical facility longer than necessary. Visitors that arrive later in the day will produce more general waste, such as newspapers and food wrappers; thus, it is advisable to collect general and recyclable debris after visiting hours has finished. An operating room generates a huge volume of potentially infectious waste; therefore, it may be necessary to have many collections a day to accommodate the operation's schedule.

4.4.7 On-Site Transport of Waste

WHO [5] has recommended that for the safety of patients and staff and to limit the number of heavy carts going through patient care areas, on-site transportation can take place at times when there are fewer people around. It is preferable to build a health-care facility with distinct floors, stairways, or elevators for waste transport and other ancillary amenities. All transportation workers should wear personal protective equipment (PPE), such as gloves and robust and closed shoes, as well as overalls and face masks. Trash should be transported in separate containers for hazardous and non-hazardous waste. It is necessary to provide trolleys that are suitable for the situation. Garbage, especially hazardous waste, should never be transported by hand due to the possibility of infection or injury from infectious material or incorrectly disposed sharps that may protrude from a container. In the event of breakdowns or maintenance, spare trolleys should be accessible. Cleaning and disinfecting the cars should be done on a daily basis. All waste bag seals must be in place and intact at the end of the transport [5].

In general, WHO [5] distinguishes three modes of transportation:

1. General waste transportation trolleys shall be painted black, used only for non-hazardous trash, and conspicuously labelled "General waste" or "Non-hazardous waste".
2. Infectious waste and used sharps trash can be carried together. To avoid the transmission of infectious agents, infectious waste should not be carried alongside other hazardous trash. Trolleys should be labelled with an "Infectious garbage" sign and coloured in the appropriate infectious waste colour code (yellow).
3. Other hazardous waste, such as chemical and pharmaceutical waste, must be transported separately in boxes to central storage facilities. Waste chutes should not be used in health-care institutions because they increase the danger of transferring airborne illnesses.

4.4.8 Off-Site Transport of Waste

The transportation of health-care trash out from a health-care facility on public streets is known as off-site transport. If hazardous health-care waste is sent across an international border for treatment, it must adhere to national rules as well as international accords. UN recommendations on the transportation of hazardous goods can be relied upon in the absence of national laws by the appropriate authorities (UN [10]). There should be sufficient training for drivers of vehicles hauling hazardous health-care waste. They must also be medically fit to operate a motor vehicle. To reduce the possibility of accidents and spillages, a designated vehicle should be employed, identified to identify its load, and its payload secured. Vehicles or containers used to transport medical waste should not be utilised to transport anything else.

4.5 Treatment and Disposal Methods of HCW

Treatment is needed to reduce the risk of HCW causing harm while conserving the environment; there needs to be a waste-management hierarchy, in which first steps are done to decrease waste and reuse it whenever possible before any other activities are taken. Unusable waste materials should be treated to reduce their volume and any health or environmental risks before being transferred for safe final disposal if this isn't possible. WHO [5] compiled information from a variety of sources on the common practice of disposing of medical waste in various parts of the world (Table 4.13).

There are a number of factors to consider, including the waste characteristics, technology capabilities and requirements, environmental and safety issues, and costs, which all vary depending on the geographical conditions in which they are implemented. All must be considered when selecting a treatment system. Sharps, pathogenic, and pathological waste are among the hazardous components of medical waste. They can be treated by various means which will be discussed in the subsequent sections. The majority of HCW produced has the potential to be contagious. One of the most well-established methods of waste management relies on the

Table 4.13 Disposal practices for medical waste in many countries throughout the world

Country	Disposal methods
Mongolia	Open dumping or open burning, incineration, autoclaving
Bangladesh	Dumping
Libya	Dumping, incineration
Greece	Recycling-reuse, pyrolytic combustion, landfill
Malaysia	Landfill, incineration, recycling
India	Landfill, incineration, autoclaving, recycling-reuse

Source: WHO [5]

disinfection method. Disease transmission can be reduced or even prevented through the practice of "disinfection", which involves reducing or removing pathogenic germs (pathogens). WHO [5] has described various treatment options of HCW. These are discussed here.

4.5.1 Incineration

4.5.1.1 Category

Incineration is a thermal treatment of waste. Heat (thermal energy) is used in these procedures to kill pathogens in the waste. This procedure is the controlled burning of waste at high temperatures. Incineration is a dry oxidation method that turns organic and combustible trash into inorganic, non-combustible stuff, reducing waste volume and weight significantly. They are representative of the majority of treatment centres in operation around the world. On-site burning has the benefit of being a quick and easy disposal technique; however, there are issues about emissions. Modern incineration has been designed to comply with the stringent limit of air emissions. There are various types of heat treatments; the most common are incinerators, pyrolysis, and gasification. The difference is mainly based on the burning temperature and the working pressure.

The temperature at which the fire burns vary depending on the type; normally, temperatures range from around 200 °C to over 1000 °C. Organic material can be destroyed in a variety of ways, including combustion, pyrolysis, and gasification. Another drawback of these technologies is the emission of combustion byproducts into the atmosphere, which produces residual ash, and the need to dispose of it. Steam, carbon dioxide, nitrogen oxides, and a wide range of volatile compounds are the primary byproducts of HCW combustion (e.g. metals, halogenic acids, incomplete combustion products), and particulate matter, as well as solid leftovers such as ashes. A typical schematic of the incineration technology is shown in Fig. 4.9.

Substoichiometric air levels are used in pyrolysis and gasification processes. Table 4.14 explains the differences between pyrolysis, gasification, and incineration. Table 4.15 compares the advantages and disadvantages of the incineration process. This is followed by Table 4.16, which details the number of incinerators for HCW management in selected countries.

4.5.1.2 Required Waste Characteristics

The basic and desirable characteristics recommended for incineration with energy recovery include (Patil [13]):

- Nett heating/calorific (value) above 1200 kcal/kg (5021 kJ/kg)
- Organic/volatile matter above 40%

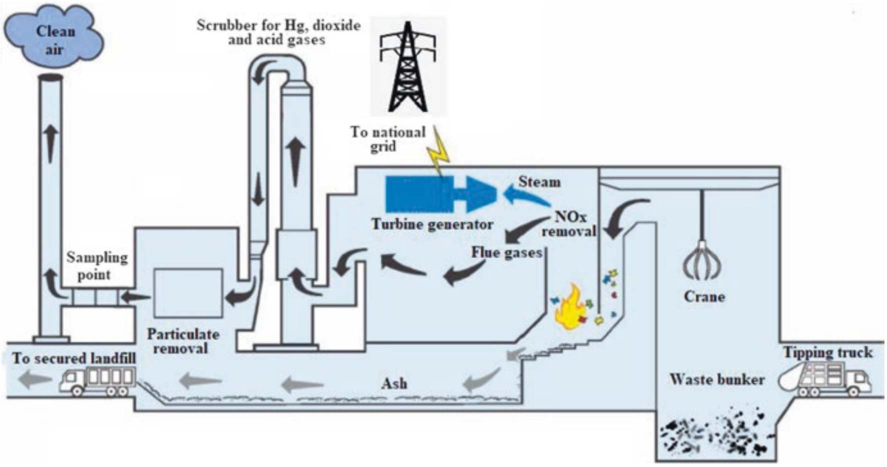

Fig. 4.9 A typical type of incinerator with energy recovery [11]

Table 4.14 Typical pyrolysis, gasification, and incineration reaction conditions [12]

	Pyrolysis	Gasification	Incineration
Reaction temperature (°C)	250–700	500–1600	800–1450
Pressure (bar)	1	1–45	1
Atmosphere	Inert/nitrogen	Gasification agent: O_2, H_2O	Air
Stochiometric ratio	0	<1	>1
Product from the process			
• Gas phase	H_2, CO, C_xH_y, H_2O, N_2	H_2, CO, CO_2, CH_4	CO_2, H_2O, O_2
• Solid phase	Ash, coke	H_2O, N_2	NO_2
• Liquid phase	Pyrolysis oil, water	Slag, ash	Slag, ash

Table 4.15 Advantages and disadvantages in applying the incineration technology. Source WHO [1]

Advantages	Disadvantages
• Significant reduction of waste volume and weight	• High energy requirement
• Ensure decontamination (combustion at minimum 800 °C temperature)	• The combustion of HCW produces mainly gaseous emissions, including steam, CO_2
• No post-treatment is needed for final disposal	• NO_x, a range of volatile substances (e.g. metals, halogenic acids, products of incomplete combustion)
	• Potential emissions of carcinogens
	• Particulate matter, plus solid residues in the form of ashes, which are to be treated as toxic

Table 4.16 Number of incinerators for HCW management in selected countries [1]

Country	Number of incinerators
Bangladesh	• 5 incinerators are installed, of which three are operating
India	• 225 incinerators installed
Indonesia	• Out of 646 hospitals dedicated to handling COVID-19 patients, 20 have their own licenced incinerators.
	• In general, there are 110 licenced incinerators in regular hospitals, located mainly in urban areas. nine incinerators, mostly damaged, with only one licenced in Bangka Belitung. two incinerators, with no licence from the Ministry of Environment and Forestry in Pangkal Pinang
Kenya	• 10 diesel operating incinerators located in high volume health-care facilities
Malaysia	• 12 incinerators for hazardous waste
Mexico	• 19 incinerators installed with capacity enough to handle 117,519 tonnes/year
Saint Lucia	• 20 small-scale pyrolysis units purchased but not installed and commissioned
South Africa	• 9 incinerators
Thailand	• 15 incinerators for infectious waste in the country
	• 62 hospitals operate their own incinerators
	• 1 incinerator at Mae Fah Luang University in Chiang Rai

Table 4.17 Key properties of HCW [1]

Parameter	Average value
Moisture content	15% by weight
Energy value (heating)	15 MJ/kg (3600 kcal/kg or 6400 BTU/lb)
Combustion residues	15% by weight
Bulk density	100–200 kg/m^3

- Content of non-combustible fines (inerts) below 15%
- Moisture content below 45%
- Fixed carbon below 15%

There are, however, minor differences in the values. According to WHO [5], incineration of garbage is only affordable and possible if the waste's "heating" (or "calorific") value is at least 2000 kcal/kg (8370 kJ/kg). While hospital wastes with high quantities of plastics can have calorific values above 4000 kcal/kg (16,740 kJ/kg), HCW can include a significant proportion of wet waste and have substantially lower calorific values. However, according to WHO [1], a greater calorific value is required for combustion (Table 4.17) [1].

Energy recovery appears to be an appealing option because many current bigger incineration facilities can reuse the heat generated by waste burning. However, this is only feasible for larger or regionally located incinerators.

4.5.1.3 Types of Incinerators for HCW

Incinerators can be as simple as a basic combustion unit or as complicated as high-temperature operational plants. All types of incinerators should be able to eliminate microorganisms from waste and reduce waste to a negligible amount of ash if handled appropriately. It is important to balance the public health benefits of removing pathogens against the technical requirements necessary to minimise the pollution in the air or groundwater from waste combustion byproducts (WHO [5]).

HCW are normally treated with one of three incineration technologies:

1. A dual-chamber starved-air incinerator, which is designed to burn infectious HCW and operates in the starved-air mode (below stoichiometric conditions) in the primary chamber
2. Multiple hearth/chamber incinerators, such as in-line incinerators and retort incinerators used for pathological waste
3. Rotary incinerators

4.5.1.3.1 Incinerators with a Lack of Oxygen

HCW is usually incinerated using a method known as starved-air incineration. Incineration processes include controlled-air incineration, pyrolysis, two-stage incineration, and static hearth incineration. Incineration air has a lower stoichiometric composition than that of the combustion process (that is, the amount of oxygen is less than the ideal proportion needed for burning carbon and hydrogen).

This type of incinerator has a primary chamber and an additional post-combustion chamber (Fig. 4.10). Ashes and gases are produced as a result of the rubbish being thermally burned in the first chamber utilising an oxygen-deficient, medium-temperature combustion process (800–900 °C). To start the process, a fuel burner is inserted into a primary chamber. There is a wide range of waste residence time, ranging from 1 h up to 4 h, depending on the installation. High temperatures (between 1100 and 1600 °C) and an abundance of air are used to burn the primary chamber's gases in the secondary chamber, reducing smoke, carbon monoxide, and odours. Any temperature below 1100 °C (the European Union's Waste incineration directive 2000/76/EC) requires additional energy to be delivered by a gas or fuel burner. Larger pyrolytic incinerators (more than 20 tonnes/day capacity) are normally intended to run continuously. They can also operate automatically, including garbage loading, ash disposal, and internal movement of burning waste.

4.5.1.3.2 Multiple Chamber/Hearth Incinerators

Pathological waste is still incinerated in several countries using multiple hearths incinerators, which were once more common. There are two primary types of incinerators: in-line and retort. Volatile organic compounds from the flue gas are

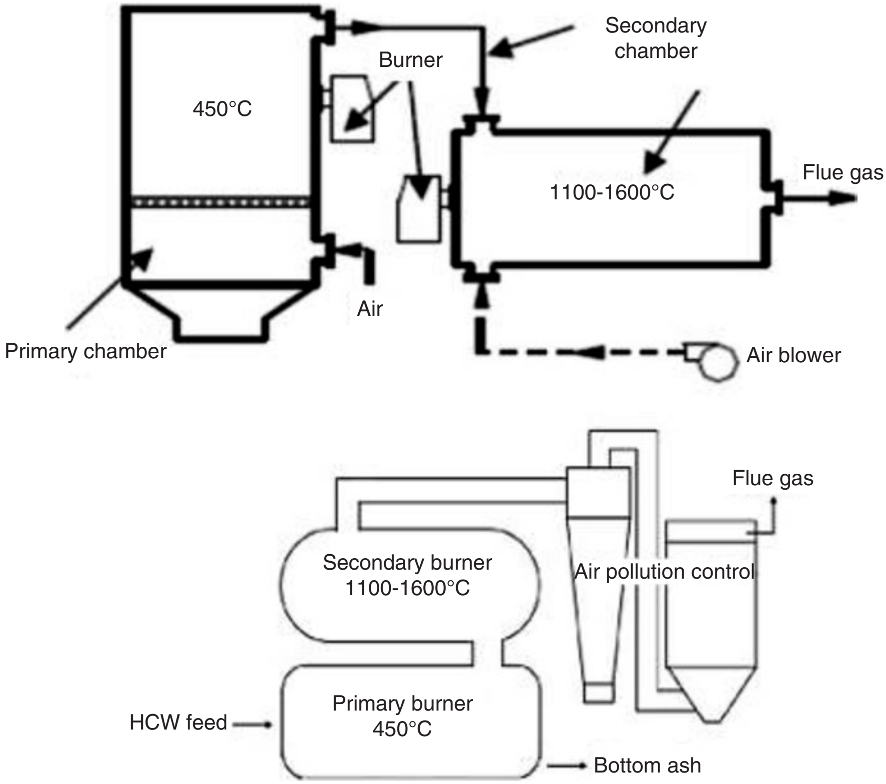

Fig. 4.10 A typical dual-chamber starved-air incinerators [5]

combusted in a secondary incinerator, and the gas is then forced to turn in different directions to remove particle matter as ash residue. The incinerators are rectangular in shape.

4.5.1.3.3 Energy-Recovering Rotary Kilns

An oven and post-combustion chamber are the two components that make up the rotary kiln [5]. As a large-scale central/regional HCW incinerator, they can also be constructed to burn chemical wastes. The proper temperatures and scrubbing equipment (used to clean the flue gas) are employed in a modern design rotary kiln.

The axis of a rotating kiln is tilted away from the horizontal (3–5% slope). Two to 5 rpm of rubbish are charged into the kiln's upper end. The ashes are then released from the bottom of the pyre. In the post-combustion chamber, the kiln-generated gases are heated to high temperatures to burn off gaseous organic components, and their residence time is typically 2 or more seconds. These machines can function at full capacity for long periods of time, and they can handle a variety of loading

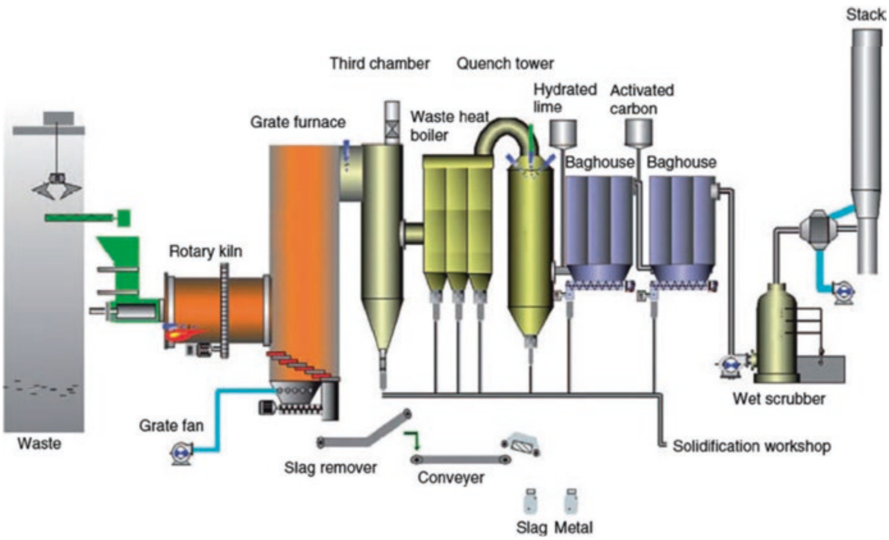

Fig. 4.11 A typical rotary-kiln incinerator [14]. (Reprinted from Jiang, X., Li, Y., Yan, J. Hazardous waste incineration in a rotary kiln: a review, Waste Disposal & Sustainable Energy, (2019) 1: 3–37 https://doi.org/10.1007/s42768-019-00001-3 with permission from Springer)

methods. Specialised trash disposal firms and industrial areas away from health-care facilities are appropriate for toxic waste treatment facilities.

Rotary kilns are normally operated at temperature ranges between 900 and 1200 °C. Its capacity of up to 10 tonnes/h is available. Its operating costs are high; however, it can be compensated with an energy recovery facility. The system also requires well-trained personnel. A typical rotary-kiln incinerator is shown in Fig. 4.11.

4.5.1.4 Environmental Control of Incinerators

In those countries that have joined the Stockholm Convention, incinerator discharges should meet national criteria and follow the Stockholm Convention's BAT, and best environmental practices (BEP) advice. If no such regulations have been developed by the competent authorities, the BAT/BEP guidelines or international standards may be used as reference (Table 4.18) (WHO [5]).

It is possible to treat flue gases with a combination of wet, dry, or semi-dry flue gas treatment processes. It is essential to keep the combustion temperature under control and to rapidly cool the exhaust gases in order to prevent dioxins and furans from reforming.

WHO [5] describes several MCW incineration specifications and operation protocols. The Stockholm Convention is a legally binding pact aimed at preventing persistent organic pollutants from harming human health and the

Table 4.18 Emission guidelines for HCW incinerators [5]

Pollutant	Unit	Standard condition	US EPA emission limits			EU emission limits			AP 42
			Small	Medium	Large	Daily ave.	Half-hour ave.	0.5–8-h ave.	
Particulate matter of total dust	mg/m^3	20 °C, 101.3 kPa, 7% O_2, dry	66	22	18				223
		273 K, 101.3 kPa, 11% O_2, dry				10	10, 30		
Carbon monoxide	ppm (v)	20 °C, 101.3 kPa, 7% O_2, dry	20	1.8	11				127
	mg/m^3	273 K, 101.3 kPa, 11% O_2, dry				50	100		
Dioxin/furans	ng TEQ/m^3	20 °C, 101.3 kPa, 7% O_2, dry	0.0013	0.014	0.035				4.1
	ng TEQ/m^3	273 K, 101.3 kPa, 11% O_2, dry						0.1	
Gaseous and vaporous organics as total organic carbon	mg/m^3	273 K, 101.3 kPa, 11% O_2, dry				10	10, 20		15
Hydrogen chloride	ppm (v)	20 °C, 101.3 kPa, 7% O_2, dry	15	7.7	5.1				1106
	mg/m^3	273 K, 101.3 kPa, 11% O_2, dry				10	10, 60		
Hydrogen fluoride	mg/m^3	273 K, 101.3 kPa, 11% O_2, dry				1	2, 4		
Sulphur dioxide	ppm (v)	20 °C, 101.3 kPa, 7% O_2, dry	1.4	1.4	8.1				54.6
	mg/m^3	273 K, 101.3 kPa, 11% O_2, dry							
Nitrogen oxides	ppm (v)	20 °C, 101.3 kPa, 7% O_2, dry	67	67	140				93
	mg/m^3	273 K, 101.3 kPa, 11% O_2, dry				200	200,400		

environment. In order to comply with the agreement, countries that are signatories must employ the greatest possible technology for new incinerators. The limits for best available technology and best environmental practices established by the Stockholm Convention limit dioxin and furan levels in air emissions to 0.1 ng I-TEQ/Nm^3 at 11% O_2. Furthermore, dioxin levels in treatment plant wastewater from any gas treatment scrubber effluents should be considerably below 0.1 ng I-TEQ/L.

The Stockholm Convention specifies primary and secondary measures for achieving dioxin and furan elimination performance levels. The following are the primary indicators:

- Only operate the combustion chamber at temperatures below 850 °C.
- Start-up and shut-down operations are handled by auxiliary burners.
- It is advised that the incinerator be run continuously.
- The oxygen supply should be continuously adjusted based on consistency of the input material's heating value.
- Secondary air or recirculated flue gas, preheating the air-streams, or regulating the air inflow, high turbulence of exhaust gases, and reduction of excess air should be maintained after the last injection of air, or at 1100 °C for wastes containing more than 1% halogenated organic compounds (usually found in healthcare waste) and 6% O_2 by volume.
- The incinerator's operation and management should be able to be monitored online from a central console, including temperature, oxygen content, carbon monoxide, and dust levels.

The secondary reduction of dioxins and furans involves a combination of dust-removal equipment and additional procedures such as catalytic oxidation, gas quenching, and wet or semi-dry adsorption systems. Fly and bottom ash, as well as wastewater, must be dealt with carefully. It is recommended that all of these parameters be checked on a regular basis in accordance with national regulations and manufacturer recommendations. These include carbon monoxide concentrations in the flue gas as well as oxygen concentrations therein, particulate matter, hydrogen chloride, sulphur dioxide, nitrogen oxides, and hydrogen fluoride.

4.5.2 Low Heat Treatment Systems

This type of non-incineration heat treatment is divided into four stages: thermal, chemical, irradiative, and biological. The bulk of non-incineration technologies employ thermal and chemical processes. The primary purpose of the treatment method is to eliminate bacteria from the waste stream. Facilities should ensure that the disinfection technique is in compliance with state regulations. Various low heat treatment systems are discussed here [5].

4.5.2.1 Heat Processes

This type of thermal technique uses elevated temperatures to kill microorganisms, but not so high that the waste will burn or pyrolyze. Thermal low-heat technologies generally operate between 100 and 180 °C. In both wet and dry circumstances, low-heat reactions can occur. Moist (or wet) thermal treatment, in which steam is used to disinfect waste, is a common practice in autoclaves and other steam-based treatment systems. Because moist heat (hot water and steam) generated by microwave energy is used to disinfect, microwave treatment is primarily a moist thermal process. Rather than using water or steam, hot air is employed in dry-heat activities.

In dry-heat systems, waste is heated using infrared or resistance heaters by conduction, irradiation, convection, and/or thermal radiation.

4.5.2.2 Chemical Processes

Various chemical disinfectants such as chlorine, dissolved chlorine dioxide, bleach (sodium hypochlorite), peracetic acid (lime solution), ozone gas, or dry inorganic compounds are utilised in this process (e.g. calcium oxide powder). A typical cleaning method in hospitals, chemical disinfection, is now being utilised to treat health-care workers. Waste is disinfected rather than sterilised when chemicals are used to kill or inactivate microorganisms. Liquid waste from hospitals, such as blood, urine, faeces, or sewage, is best treated with chemical disinfection methods. However, they can still be employed in the remediation of solid wastes. Microorganisms, pollution, disinfectant concentration and quantity, as well as contact time and mixing requirements, are all factors that must be taken into account when it comes to optimal utilisation of wastes.

Shredding, grinding, and mixing are typically required in chemical processes to maximise the waste's exposure to the chemical agent. Grinding ensures that the chemical agent is exposed to all areas of the waste and facilitates the disposal of any residues. In liquid systems, the disinfectant may be removed and recycled by passing the waste through a dewatering portion. In addition to chemical disinfectants, encapsulating chemicals can solidify sharps, blood, or other bodily fluids in a solid matrix before disposal. Another example of a chemical process is the use of heated stainless-steel tanks to break down tissues, pathological debris, anatomical components, and animal corpses using hot alkali.

4.5.2.3 Irradiation Technologies

Electron beams, cobalt-60, and ultraviolet irradiation are all examples of irradiation treatments. Gamma radiation, emitted by cobalt, kills all the germs in waste. The expensive cost of cobalt and the high operating costs have hindered commercial ventures from utilising this technology for the treatment and management of medical waste. Controversy has also arisen over the method of cleaning the substance using radiation. As with autoclaving and microwave methods, it is not recommended for pathological wastes.

To avoid increased occupational exposures to electromagnetic radiation, these devices require shielding. The amount of waste material absorbed by pathogens determines the effectiveness of pathogen killing. Waste bags and containers can be pierced by electron beams. It is possible to use germicidal ultraviolet radiation as a supplement to conventional disinfection methods; however, it cannot penetrate tight garbage bags.

4.5.2.4 Biological Processes

These processes can be found in natural living creatures; however, when used for HCW treatment, they pertain to the decomposition of organic materials. To speed up the degradation of pathogen-containing organic waste, certain biological treatment systems employ enzymes. Composting and vermiculture (worm-assisted digestion of organic waste) are biological methods that have been effectively employed to decompose hospital food garbage, together with other organic digestible waste and placenta waste [15]. Another biological process is the spontaneous breakdown of pathological waste by burial.

4.5.2.5 Mechanical Processes

Shredding, grinding, mixing, and compaction technologies are examples of mechanical treatment techniques that reduce waste volume but do not remove pathogens. Mechanical techniques are rarely used as stand-alone HCW treatment methods but rather as a supplement to other treatment methods. Mechanical destruction, which can be employed to disintegrate needles and syringes, can render trash unidentifiable (depending on the type of shredding). In thermal or chemical treatment methods, mechanical devices such as shredders and mixers can increase the pace of heat transfer or expose a larger surface area of garbage to waste treatment. The level of management and maintenance needed to treat HCW safely and effectively increases dramatically when mechanical devices are employed to prepare wastes before other types of waste annihilation. After disinfecting the incoming HCW waste, shredders, mixers, and other mechanical devices should be used.

4.5.2.6 Steam Treatment Technologies

WHO [5] has detailed autoclave and microwave technology for HCW treatment. These are discussed as follows.

4.5.2.6.1 Autoclaves

Autoclaves are used to disinfect and sterilise items in a physical manner. Medical autoclaves have been used for over a century to sterilise medical items. They've also lately been adopted for the treatment of infectious waste. They use a combination of steam, pressure, and time to accomplish their goals. Autoclaves kill bacteria and spores by using high temperatures and pressure. They're utilised to sterilise media, tools, and labware as well as decontaminate biological waste. Before being disposed of, medical waste that may contain bacteria, viruses, or other biological material should be autoclaved to kill any bacteria, viruses, or other biological material.

The most often used alternative to incineration is autoclaving, also known as steam sterilisation. It is a low-heat thermal process that uses steam to disinfect waste by putting it into direct contact with it for a predetermined period of time. It is both less expensive and has no known health risks. Prior to disposal in a landfill, wastes are sterilised or disinfected using this process. In hospitals, autoclaves are typically used to sterilise reusable medical equipment. Waste from patient care (such as gauze, bandages, and gowns) can be sterilised in an autoclave, including cultures and stocks, sharps, objects contaminated with blood, and limited amounts of fluids and laboratory rubbish (excluding chemical waste). They are, however, commonly applied for small amounts of waste, particularly highly infectious waste like sharps and microbial cultures. About 90% of regulated medical wastes, particularly microbiological wastes, can be autoclaved. Cytotoxic, pathological, or other toxic chemical wastes, on the other hand, are not suited for autoclaving. In general, autoclave sterilisation achieves a 99.99999% inactivation of pathogens.

High-pressure metal containers are used in autoclaves, which have sealed doors and pipelines for steam to enter and exit. Autoclaves are used to sterilise food, medicine, and other items. An important factor in the effectiveness of steam treatment is air's ability to act as an insulator. To enable heat penetration into the waste, air must be removed from the autoclave. To avoid the emission of pathogenic aerosols, waste treatment autoclaves must treat the air that is withdrawn at the start of the operation, unlike instrument sterilisation autoclaves. This is commonly accomplished by steaming the air or putting it through an air filter before releasing it.

Pressure pulse, gravity-displacement, and pre-vacuum autoclaves are the most common types of autoclaves used for HCW treatment. Autoclaves for waste treatment can be as small as 20 L and as large as 20,000 L. Low-heat thermal processes emit far fewer pollutants into the atmosphere than high-heat thermal processes. In a gravity-displacement autoclave, steam is injected into the chamber under pressure, driving the air downwards into the chamber's outlet port. Before injecting steam, a pre-vacuum (also known as high-vacuum) autoclave uses a vacuum pump and/or a steam ejector to remove air from the chamber. It is more effective, but it is also more expensive. Because this procedure is more efficient at eliminating air and disinfecting waste, it takes less time to disinfect. A simplified concept of a pre-vacuum autoclave is shown in Fig. 4.12.

In a pressure pulse autoclave, pressure pulsing is utilised to eliminate the air. Gravity, vacuum pulsing, and pressure-vacuum are the three main types of pressure

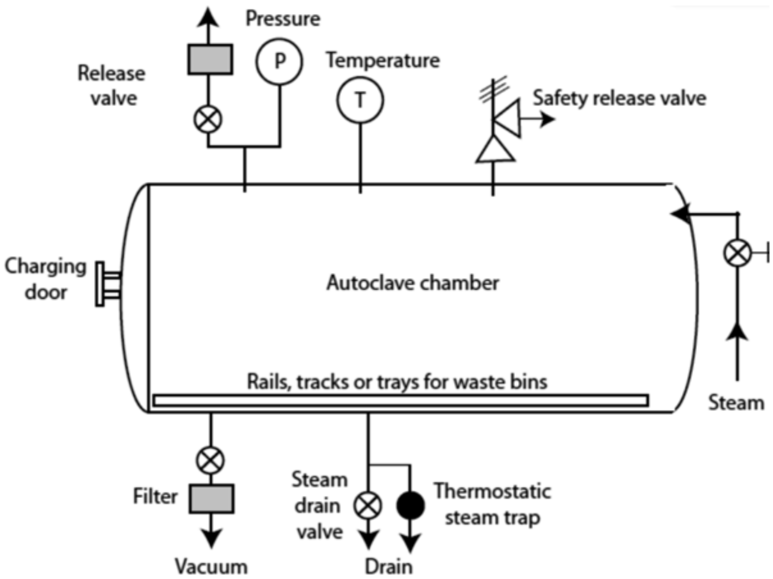

Fig. 4.12 Simplified schematic of a pre-vacuum autoclave. (WHO [5])

pulsing systems. After a predetermined level of pressure has been attained, pressure gravity (also known as steam flushing) is used to release steam and bring the pressure back up to a predetermined level. It is comparable to a high-vacuum method, except that it uses two or more vacuum cycles at the beginning of the therapy. During therapy, the pressure is increased, and the vacuum is released multiple times, which is how pressure-vacuum systems work. Steam penetration is accelerated by using alternating pressure cycles. Pressure vacuum systems, in general, have the quickest time to achieve high disinfection standards.

When using an autoclave for disinfection, make sure you have the right combination of temperature/pressure and time in there. One to 2 bar (approximately 15–30 psi, or 1540–2280 mmHg absolute) gauge pressure is required for waste treatment autoclaves. Previously, while using saturated steam, a 30-min maximum exposure time limit was established at 121 °C. This translates to a minimum pressure of 205 kPa (2.05 bar) (15 psi). Psi-pound per square inch is an abbreviation in the list of abbreviations. The load's composition and volume may necessitate a longer cycle time.

Temperature and pressure, process sequence, load size and stacking configuration and packing density; types and integrity of bags or containers used; waste materials (such as bulk density, heat capacity and thermal conductivity), the amount of residual air, and the moisture content of the waste [16] influence the performance of an autoclave system. When sterilising liquids, such as blood or urine bags, the sterilisation technique and time must be altered.

Autoclave trash retains its physical appearance. After treatment, the garbage may be rendered unrecognisable using a mechanical technique such as shredding or

Table 4.19 The advantages and disadvantages in the autoclave technology [1]

Advantages	Disadvantages
• Suitable for soiled wastes, bedding and personal, protective equipment, clinical laboratory waste, reusable instruments, waste sharps, and glassware	• Cannot treat volatile and semi-volatile organic compounds, chemotherapeutic waste, mercury, other hazardous chemical and radiological waste, large and bulky bedding material, large animal carcasses, sealed heat-resistant containers
• Low-heat thermal processes produce significantly less air pollution emissions than high-heat thermal processes	• Odours can be a problem around autoclaves if there is insufficient ventilation
• No specific pollutant emissions limits for autoclaves and other steam treatment systems	• Poorly segregated waste may emit low levels of alcohols, phenols, formaldehyde, and other organic compounds into the air
• Waste does not require further processing; it can be disposed of on a municipal landfill as it is disinfected and not hazardous anymore. However, some countries request to render the waste unrecognisable, then it is shredded afterwards, but this depends on the legal regulation	• Treated waste from an autoclave retains its physical appearance
• Available in various sizes from lab autoclaves to large autoclaves used in large waste treatment facilities	• Waste requires further processing for final disposal

Source: [1]

grinding. Shredding can reduce the volume of treated waste by 60–80%; however, it has a high failure rate.

For almost a century, autoclaves have been used to sterilise medical instruments, and they have only lately been used for the treatment of infectious waste. An autoclave consists of a metal container built to resist high pressures, a sealed door, and a set of pipes and valves that allow steam to enter and escape the container. The advantages and disadvantages of autoclave technology are listed in Table 4.19 [1].

4.5.2.6.2 Microwave Treatment Technologies

Patients are often treated with moist heat and steam generated by microwave energy in the majority of microwave-based treatments. With a frequency of 2450 MHz and a wavelength of 12.24 cm, microwave energy quickly heats water in the waste [1].

Sterilising garbage with microwaves is another application for this cutting-edge technology. Patients are often treated with moist heat and steam generated by microwave energy in the majority of microwave-based treatments. The thermal activity of electromagnetic radiation energy with a frequency range ranging from 300 to 300,000 MHz rapidly heats the water in the trash. Microwaves at a frequency of 2450 MHz and a wavelength of 12.24 cm kill the majority of microorganisms. Intermolecular heating is a type of microwave heating. To neutralise any biologicals

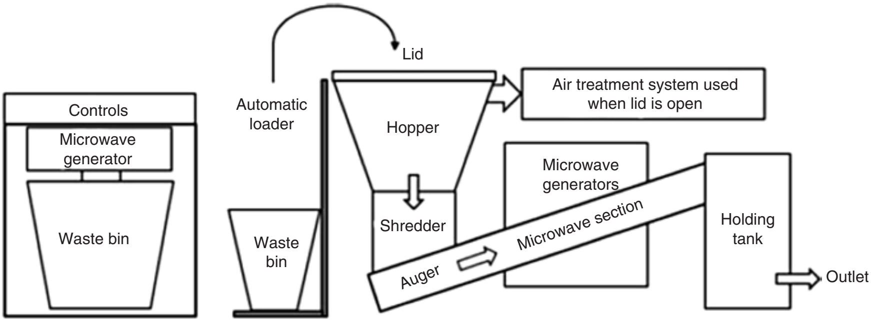

Fig. 4.13 A schematic diagram of a batch and semi-continuous microwave system. (WHO [5])

present, garbage is shredded first, then mixed with water and heated within. Pathogenic components are eliminated via heat conduction when microwaves instantly heat the water enclosed within the waves. This procedure, which is comparable to autoclaving, can manage approximately 90% of medical wastes. According to reports, shredding reduces volume and uses less energy than an incinerator.

A microwave generator delivers microwave energy into a treatment area or chamber in most microwave treatment systems (magnetron). Two to six magnetrons, each with an output of roughly 1.2 kW, are commonly utilised in batch or semi-continuous processes. Batch systems have a capacity of 30–100 L, making them ideal for large-scale waste management. Depending on the therapist, a session might take anywhere from 30 min to an hour.

Automated charging, hopper, shredder, conveyor screw, and steam generator are some of the components of a typical semi-continuous microwaving system (Fig. 4.13). Waste bags are put into the hopper, which may be steam sprayed. The air is evacuated by a filter as the waste bags are loaded, preventing the spread of airborne germs. Once the hopper cover is closed, the waste is shredded. Before being heated to 100 °C by four or six microwave generators, waste particles are transported by an auger (conveyor screw). It is possible to shorten the exposure time by using a holding segment. A secondary shredder may be used if treated sharps require finer shredding. A semi-continuous microwave system on a big scale can treat roughly 250 kg of food every hour (3000 tonnes/year).

Some common waste categories include cultures and stocks, sharps and things contaminated with blood or body fluid, isolation/operation/lab trash (excluding chemical waste), and soft waste (e.g. gauze, bandages, gowns, and bedding) from patient care that are commonly treated in microwave systems. Non-volatile organic chemicals, chemotherapeutic waste, mercury, other hazardous waste and radioactive materials should not be treated with microwaves. It is possible to prevent the release of aerosols during the feed process by using a fully enclosed microwave unit equipped with an effective filter. The advantages and disadvantages of microwave technology are given in Table 4.20 [1].

Table 4.20 The advantages and disadvantages of microwave technology [1]

Advantages	Disadvantages
• Suitable for soiled wastes, bedding and personal, protective equipment, clinical laboratory waste, reusable instruments, waste sharps and glassware	• Volatile and semi-volatile organic compounds, chemotherapeutic waste, mercury, other hazardous chemical waste and radiological waste should not be treated in a microwave
• A fully enclosed microwave unit can be installed in an open area and used with a HEPA filter to prevent the release of aerosols during the feed process	• Treated waste from an autoclave microwave unit retains its physical appearance
• Odour is somewhat reduced, except in the immediate vicinity of the microwave unit	• Waste requires further processing for final disposal
• A large-scale, semi-continuous microwave unit is capable of treating about 250 kg/h (3000 tonnes/year)	• Very limited volume reduction, no weight reduction
• Waste does not require further processing. It can be disposed of on a municipal landfill as it is disinfected and not hazardous anymore. However, some countries request to render the waste unrecognisable, then it is shredded afterwards, but this depends on the legal requirement	
• Available in various sizes from lab autoclaves to large autoclaves used in large waste treatment facilities	

4.5.3 Encapsulation and Solidification

As detailed in [5], untreated HCW should not be disposed of in municipal landfills. The HCW should confine the waste before it is disposed of if there is no other option. Examples of encapsulation include filling containers with waste and adding an immobilising chemical before sealing them. Sharps, chemicals, or pharmaceutical residues are collected in either high-density polyethylene cubic boxes or iron drums. The containers or boxes are then filled with a medium such as plastic foam, bituminous sand, cement mortar, or clay material. On drying, the containers are sealed and disposed of in landfills.

To use this method, you must have access to encapsulating materials that can be used to dispose of sharps and chemical or medicinal leftovers. Encapsulation alone is not recommended for non-sharps waste, although it can be used in conjunction with other treatment methods. Scavengers are less likely to be able to get their hands on HCW waste if the procedure is used. To use this method, you must have access to encapsulating materials that can be used to dispose of sharps and chemical or medicinal leftovers. Encapsulation alone is not recommended for non-sharps waste, although it can be used in conjunction with other treatment methods. Scavengers are less likely to be able to get their hands on HCW waste if the procedure is used.

Solidification is the process of combining garbage with cement and other materials before disposal to reduce the possibility of harmful compounds in the waste transported into and polluted the surface or groundwater. It's especially good for pharmaceuticals and high-metal-content cremation ashes (the procedure is known as "stabilisation" in this case). The packaging should be removed, the medications crushed, and a mixture of water, lime, and cement added to solidify pharmaceutical waste. Onsite, a homogeneous mass is generated, and cubes (for example, 1 m^3) or pellets are manufactured. These can then be relocated to an appropriate storage location. Alternatively, the homogenous mixture can be carried to a landfill in a liquid form and put on top of previously landfilled municipal garbage before being topped with new municipal waste.

WHO [5] states that the average proportions (by weight) of the combination are 65% pharmaceutical waste, 15% lime, 15% cement, and 5% water. Cost-effective and easy-to-use mixing equipment are the main advantages of this method. Other than manpower, the essentials include a grinder or road roller to break up the stones, a concrete mixer, and a supply of cement, lime, and water.

4.5.4 Emerging Technologies

Because most current and emerging technologies do not have a track record in HCW applications, WHO [5] recommends that they be carefully examined before being adopted for routine use. Ozone, promession, and plasma pyrolysis are the most commonly discussed technologies in scientific literature. Using plasma arc torches or electrodes, plasma pyrolysis generates temperatures in excess of a million degrees Fahrenheit from electrical energy. In an atmosphere with little or no air, high temperatures are employed to pyrolyze waste. Another new method breaks down the pathogenic, toxic chemical, or pharmaceutical wastes with superheated steam at 500 °C. The vapours are then heated to 1500 °C in a steam reforming chamber. As with incineration, these processes are costly and require pollution control systems to remove impurities from exhaust gas before they can begin. Waste can be disinfected with ozone (O_3). Ozone gas is a powerful oxidant that degrades quickly into a more stable state (O_2). Shredders and mixers are necessary for ozone systems because they expose waste to the bactericidal agent. Uses for ozone include curing water and removing odours. Ozone can irritate the eyes, nose, and respiratory tract at quantities greater than 0.1 ppm. To ensure that the microbial inactivation criteria are met, regular testing should be performed, exactly like with other chemical treatment technologies.

Promession is a revolutionary technology for destroying anatomical waste that combines a mechanical process with heat removal. Human remains are disintegrated into powder utilising cryogenic freeze-drying with liquid nitrogen and mechanical shaking before being buried. The technique accelerates decomposition, reduces bulk and volume, and allows metal pieces to be recovered. Other emerging technologies include gas-phase chemical reduction, base-catalysed decomposition, supercritical water oxidation, sodium reduction, vitrification, superheated steam reforming, ozonation, biodegradation, mechanochemical treatment, sonic technology, electrochemical technologies, solvated electron technology, and phytotechnology [17, 18].

4.5.5 Gas Sterilisation

Heat-stable materials are employed in the majority of medical and surgical devices in health-care facilities, and steam is used to sterilise them. However, since the 1950s, there has been an increase in low-temperature sterilisable medical devices and tools (e.g. plastics). Gas sterilisation uses a sterilising chemical (such as ethylene oxide or formaldehyde) to treat medical waste that has been pumped into an evacuated, airtight chamber (WHO [4]). The gas will kill any hazardous or infectious agents that come into touch with the garbage.

Ethylene oxide gas has been used in heat and moisture-sensitive medical equipment since the 1950s. Medical devices can now be sterilised using a variety of low-temperature sterilisation methods (e.g. hydrogen peroxide gas plasma, immersion in peracetic acid, ozone, etc.). Sterilisation removes all germs from a product's surface or fluid to avoid disease transmission associated with its use [19]. The EPA does not recommend ethylene oxide for treating infectious wastes in countries like the United States because of its toxicity.

4.5.6 Land Disposal

After reduction or treatment, all waste systems will normally be sent to land for final disposal of the leftover HCW components. When a town or health-care facility does not have the means to treat trash prior to disposal, the direct use of a landfill is likely to be necessary. "Safe burial" will continue to be used for the disposal of HCW until adequate capacity for incineration, or other treatment options are available, particularly in many middle- and lower-income countries. At many medical facilities, hazardous waste (HCW) is accumulated and then burned or dispersed about the property. Even if the land disposal site is not established to the exacting standards utilised in higher-income areas, this poses a significantly greater risk of infection spread than regulated disposal in a landfill.

The ashes from the hazardous waste and HCW waste incineration facilities, as well as waste that is not suitable for burning, must be dumped in a secure landfill. A secured landfill is a specially designed region where waste goods are deposited. A secure landfill is often a hole in the earth; however, it can also be constructed above ground. A secured landfill's objective is to avoid any watery interaction between waste items and the natural environment. It is critical that groundwater does not generate runoff onto the surrounding environment. Hazardous and HCW waste is buried in safe landfills, while it is occasionally injected far underground in deep well injection systems.

The safe landfill, which was designed and built to the greatest of requirements, is used to dispose of both scheduled and hazardous garbage. For optimal safety, a minimum of two impermeable and chemically resistant liner systems are typically erected, with the facility itself resting on a strong geological barrier. Proper operation and maintenance of the landfill would ensure that this landfill pose no negative effects on the environment or on the people who work there. Heavy metals and other hazardous compounds are removed in the wastewater treatment facility after leachate from the secured landfill is pre-treated in a chemical treatment step.

4.6 HCW Management in Selected Countries

This section discusses HCW management in selected countries in Asia and Europe.

Medical waste is classified as B3 trash in Indonesia, according to Prasetiawan [20], and its management is governed by Government Regulation Number 101 of 2014 about the Management of Hazardous and Toxic Waste. The Minister of Environment and Forestry Regulation No. 56 the Year 2015 about Procedures and Technical Requirements for the Management of Hazardous and Toxic Waste from Health Care Facilities regulates the treatment of medical waste.

According to the Ministry of Environment and Forestry (KLHK), medical waste treatment facilities for health-care facilities in Indonesia have a capacity of 70.21 tonnes/day [20]. Furthermore, third-party processing services have a capacity of 244.08 tonnes/day (Soemiarno [21]). There are 2889 hospitals, 10,062 health centres (puskesmas), 7641 clinics, and other institutions like health laboratories, pharmacies, and blood transfusion units in total. Every day, Indonesia is expected to create 294.66 tonnes of medical waste (Nurali [22]). The government is attempting to expand the country's capacity for processing medical waste.

The government's efforts to close the gap in Covid-19 medical waste capacity should be commended. However, there are a few points that should be considered in light of this statement. Incinerators are still used in processing technology. Many elderly hospital incinerators in Indonesia, on the other hand, face a significant issue in achieving optimal combustion temperature (850–1200 °C). The lack of proper air pollution control continues to be a problem. Because of the possibility of mercury and dioxin emissions, some have been abandoned (Damanhuri [23]). The government has taken a number of steps to close the gap in medical waste treatment capacity, including optimising basic capacity and expanding reserve capacity such that total capacity reaches 877.26 tonnes/day, roughly three times reserve capacity. Medical waste management technology that isn't solely based on burning is also in the works.

Two hundred and ninety metric tonnes of medical waste are generated each day by Indonesia's 2820 hospitals and 9884 community health centres (Puskesmas), according to data from the Health Ministry, according to a report in the Jakarta Post [24]. Only 87 hospitals in Indonesia have on-site incinerators with a combined daily capacity of up to 60 tonnes, despite the fact that ten licenced medical waste processing plants have a combined daily capacity of 170 tonnes. The Environment and Forestry Ministry predicted that medical waste would rise as a result of the extensive use of protective gear and other single-use medical equipment during the pandemic. There is no evidence on how much medical waste was generated as a result of Covid-19. Medical waste generated by the 132 Covid-19 referral hospitals and the growing use of face masks and gloves by the general population is not to be overlooked.

India is a country where biomedical waste was handled and disposed of at a rate of 530 metric tonnes/day in India in 2018. This was only 20 metric tonnes fewer than the entire amount of rubbish produced that year. The most important phase in biological waste management is waste separation (Figs. 4.14 and 4.15). Some of the most usual places to find this waste are hospitals, private clinics, nursing homes as well as medical research institutes and funeral homes.

In China, in 2019 (Fig. 4.16), around 5600 metric tonnes of medical waste was produced in Shanghai in China. The 196 big and medium cities involved produced a total amount of around 843,000 of medical waste that year [26].

There are five categories of HCW in Malaysia: clinical waste (CW), radioactive waste (RW), chemical waste (CW), pressurised containers (PC), and general rubbish (GW) (Department of Environment [27]). CW is any waste that contains or has been in contact with any of the clinical waste types or that has been mixed with any of the clinical waste types, including human or animal tissue, blood or body fluids, excretions, drugs, pharmaceutical products, soiled swabs or dressings, syringes, needles, or sharps (Department of Environment [27]).

Malaysia's health ministry defines the following items as hazardous waste: (1) wastes containing human or animal tissue or blood or other body fluids, excretions, pharmaceutical drugs, or other items such as swabs or dressings, needles, or other sharp instruments; and (2) any other waste resulting from medical procedures. Table 4.21 provides the classification of HCW, which is designed for use in the health-care industry in Malaysia.

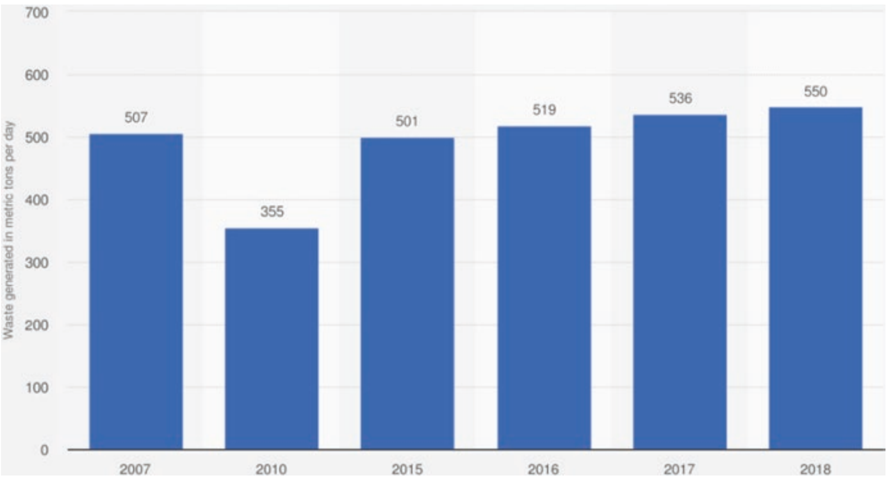

Fig. 4.14 Volume of biomedical waste generated in India from 2007 to 2018 (in metric tonnes per day) [25]

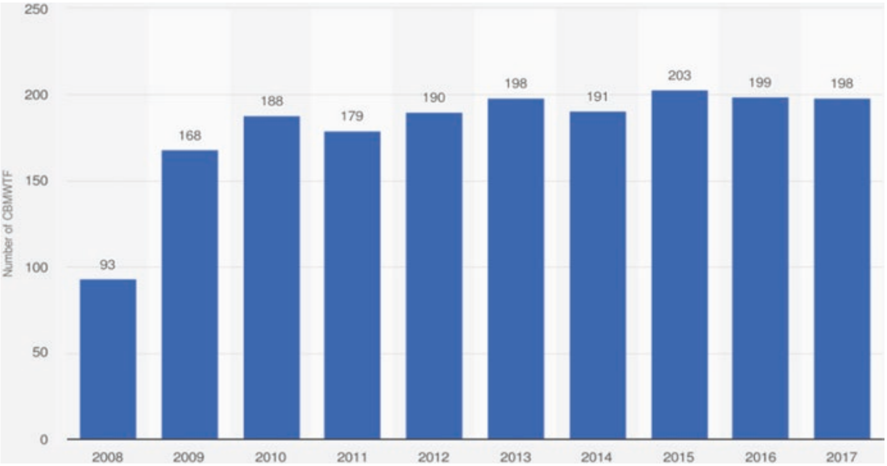

Fig. 4.15 Common biomedical waste treatment facilities (CBMWTF) in India from 2008 to 2017 [25]

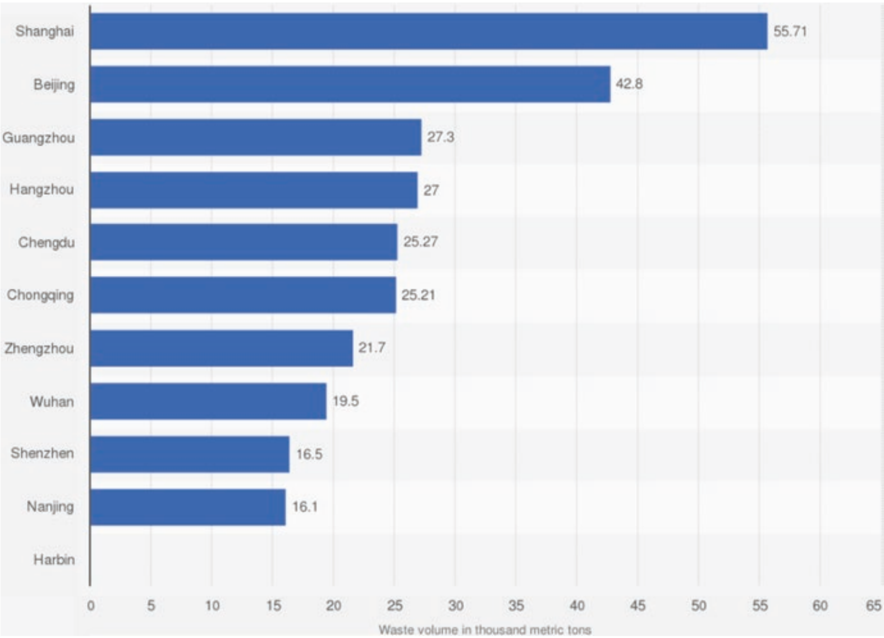

Fig. 4.16 Production volume of urban medical waste in China in 2019, by leading city (in 1000 metric tonnes) [26]

Table 4.21 Major clinical waste classifications and management recommendations in Malaysia [27]

Description	Waste management guidance
1. Blood and body fluid waste	
(a) Soiled surgical dressings, e.g. cotton wool, gloves, swabs. All contaminated waste from the treatment area. Plasters, bandages that have come into contact with blood or wounds, cloths and wiping materials used to clear up body fluids and spills of blood.	Special requirement on the management from the viewpoint of infection prevention. These categories of waste must always be incinerated completely in an appropriate incinerator.
(b) Material other than reusable linen, from cases of infectious diseases (e.g. human biopsy materials, blood, urine, stools).	
(c) Pathological waste, including all human tissues (whether infected or not), organs, limbs, body parts, placenta and human foetuses, animal carcasses and tissues, from laboratories and all related swabs and dressings.	
2. Waste posing a risk ("sharps")	
All objects and materials which are closely linked with health-care activities and pose a potential risk of injury and/or infection, e.g. needles, scalpel blades, blades and saws or any other instruments that could cause a cut or puncture.	Collected and managed separately from other waste. The collection container must be puncture resistant and leak-tight. This category of waste has to be disposed of/destroyed completely to prevent the potential risk of injury/infection.
3. Infectious wastes	
Clinical waste arising from laboratories (e.g. pathology, haematology, blood transfusion, microbiology, histology) and post-mortem rooms, other than waste included in category 1 waste.	Special requirement on the management from the view point of infection prevention. This category of waste must always be incinerated completely in an appropriate incinerator.
4. Pharmaceutical and cytotoxic pharmaceutical wastes	
(a) Pharmaceuticals which have become unusable for the following reasons:	
• Expiry date exceeded;	Class I—pharmaceuticals such as camomile tea, cough syrup, and the like which pose no hazard during collection, intermediate storage and waste management:
• Expiry date exceeded after the packaging has been opened or the ready-to-use preparation prepared by the user; or	Managed jointly with municipal wastes.
• Use is not possible for other reasons (e.g. call-back campaign).	Class II—pharmaceuticals that pose a potential hazard when used improperly by unauthorised persons:

(continued)

In Malaysia, the composition of health is mainly non-infectious waste (80%),

Table 4.21 (continued)

Description	Waste management guidance
ii.ii. (b) Wastes arising in the use, manufacture and preparation of, and in the oncological treatment of patients with, pharmaceuticals with a cytotoxic effect (mutagenic, carcinogenic, and teratogenic properties).	Managed in an appropriate waste disposal facility.
	Class III—Heavy metal containing unidentifiable pharmaceuticals: managed in an appropriate waste disposal facility.
	Intermediate storage of these wastes takes place under controlled and locked conditions. For reasons of occupational safety, cytotoxic pharmaceutical wastes must be collected separately from pharmaceutical waste and disposed of in a hazardous waste incineration plant.
5. Other infectious waste	
All health-care waste known or clinically assessed by a medical practitioner or veterinary/surgeon to have the potential of transmitting infectious agents to humans or animals. Used disposable bed-pan liners, urine containers, incontinence pads, and stoma bags.	Disposed of in a hazardous waste incineration plant licenced by the Department of Environment Malaysia.

Table 4.22 Composition of the HCW in Malaysia [28]

Type of waste	Composition
Non-infectious waste	80
Pathology waste	15
Sharps	1
Chemical and Pharmaceuticals waste	3
Other waste	1

followed by pathology waste (15%) (Table 4.22) [28].

To protect health-care professionals, waste collection employees, patients, and the general public, Malaysia has taken thorough steps to minimise practices by formulating and implementing suitable regulations and guidelines to integrate safety and health aspects in HCW. The Environmental Quality (Scheduled Wastes) Regulations 2005 [29], classify the HCW as a scheduled waste. These guidelines provide information on how to properly handle and manage health-care waste from hospitals and other health-care facilities (public and private). Under the regulations, different waste codes are employed, as detailed in subsequent sections.

The Malaysian government has opted to privatise a comprehensive HCW waste collection, transportation, and disposal system for all government hospitals because of the growing concern about the need for proper HCW management. Private health-care facilities must also ensure that their clinical wastes are properly

Table 4.23 Segregation of health-care solid waste in most hospitals in Malaysia

Category of waste	Example	Segregation
Non-clinical waste	Health-care waste that is not in contact with patient care and does not pose any hazard rather than recyclable waste such as discarded paper, plastic, etc.	Black colour plastic bag.
Infectious waste	Tissues, materials, or equipment that has been in contact with patient care.	Yellow colour plastic bag.
Sharp	Syringes, needles, scalpels, blades, cartridges, broken ampules, spike of drip set.	Sharp bin
Pharmaceutical	Time-expired drugs, used vaccine vial, drugs that have been spoilt or contaminated.	Yellow colour plastic bag.
Recyclable waste	Book, magazine, office paper, newspaper, plastic and tin, etc.—those are not contacted with patient care and do not pose any hazard.	Green colour plastic bag.

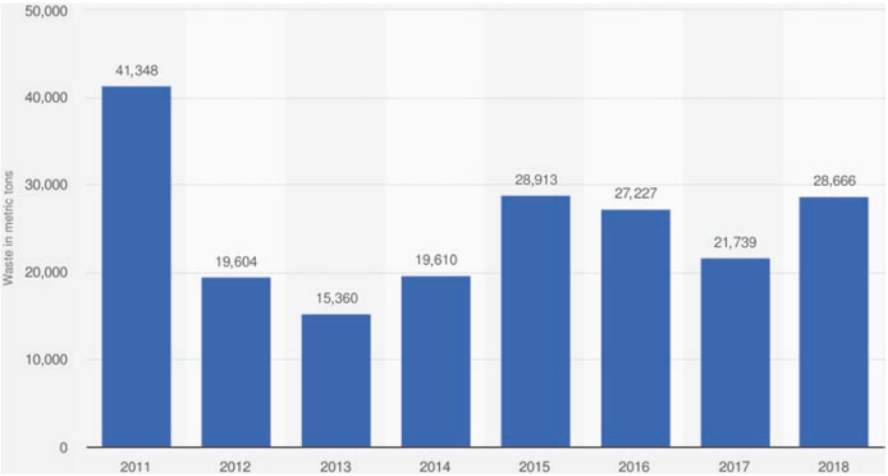

Fig. 4.17 Waste management in Spain from 2011 to 2018 for medical and biological waste (in metric tonnes) [30]

managed. Table 4.23 shows an example of how HCW wastes are segregated in most hospitals in Malaysia prior to the final disposal.

From 2011 to 2018, Fernández [30] reported the annual medical and biological waste processed in Spain in metric tonnes (Fig. 4.17). This particular form of garbage accounted for 28.7 thousand metric tonnes in total.

4.7 Legal Framework, Regulations, and Code of Practices of HCW Management

The correct segregation, storage, disposal, and documenting of waste are the core elements of HCW legislation. Through its colour-coding system, the authorised department in each country gives best practice standards for trash segregation and disposal. It is suggested that distinct waste streams be assigned different colours in order to make garbage management easier and more efficient. The colour code can be used from the time trash is generated until it is stored, transported, and disposed of.

Figure 4.18 [1] shows the global share of nations that have adopted HCW management laws as of 2020, broken down by region. Around 39% of Asian countries had passed specialised legislation on HCW management by 2020, making it one of the world's highest percentages. However, the same region had a similar proportion of countries with no HCW management plans in place. As of 2020, little more than half of the countries in the globe had some type of legislation addressing HCW management. This is especially important in light of the COVID-19 epidemic. Figure 4.19 depicts the common hierarchy of the regulatory and administrative framework for hospital waste management [5].

To see some of the examples, the legislations in the United Kingdom and Malaysia are discussed here. Their applications are generally not so much different as the case of other countries.

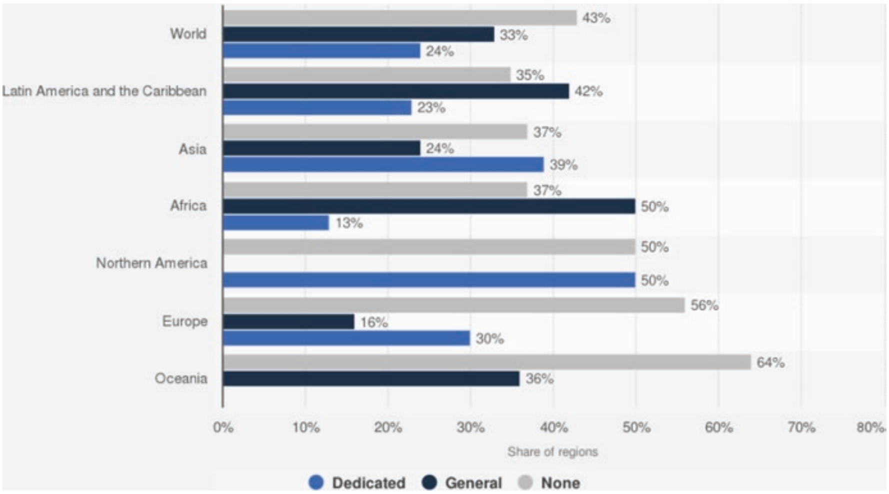

Fig. 4.18 Share of countries with adopted health-care waste (HCW) management legislation worldwide as of 2020 [1]

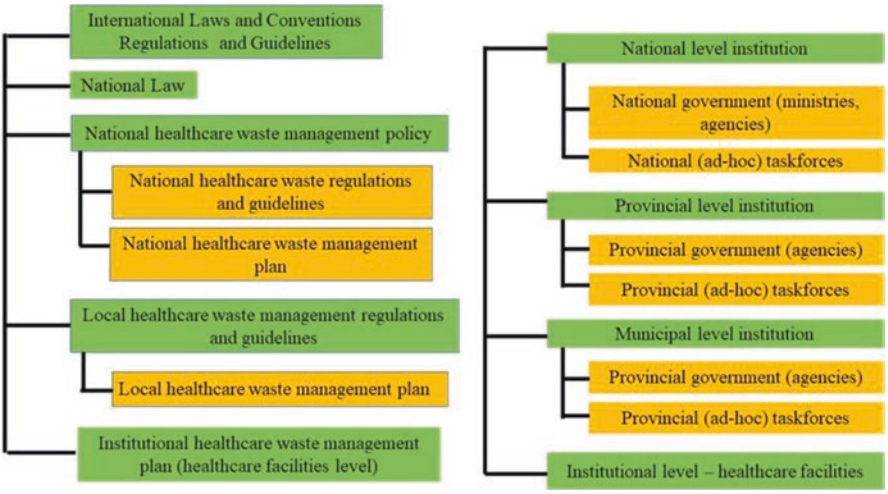

Fig. 4.19 The HCW management framework's common regulatory and institutional hierarchy [5]

4.7.1 United Kingdom

Over the years, the United Kingdom has enacted a number of regulations that address a variety of issues, including packaging and transportation, treatment, and staff health and safety. The following are the most important regulations that apply to HCW in the United Kingdom.

4.7.1.1 The 1990 Environmental Protection Act Was Enacted to Protect the Environment (Including Duty of Care Regulations)

This is the principal legislation controlling hospital waste management. Health-care providers have a Duty of Care to ensure proper waste management, which includes recording waste transfers and ensuring garbage is treated properly. It also necessitates adherence to the Waste Hierarchy. The Environmental Protection Act of 1990 was enacted as a piece of law. This legislation lays out strategies to manage trash in a way that prevents pollution of the land, water, and air. It imposes a duty of care on all businesses that produce or dispose of garbage, requiring them to do it in a safe manner. It also includes information on litter, public nuisances, and the regulation of certain substances.

4.7.1.2 The Hazardous Waste Directive (HazWaste Directive) of 2011

From trash creation through final recovery and disposal, this includes guidance on labelling, record-keeping, monitoring, and control duties. To protect the environment and human health, it prohibits the combination of hazardous substances and objects.

4.7.1.3 The Controlled Waste Regulations (England and Wales) 2012

Household, industrial, and commercial trash are classified as "regulated waste" and are governed by the Environmental Protection Act of 1990. This act was enacted in 2012 to designate specific waste types. Any industrial, commercial, or home waste is classified as controlled waste. As a result, they are governed under the Environmental Protection Act of 1990. Sewage and septic tank sludge are two examples of non-controlled waste.

4.7.1.4 Regulations for the Transportation of Dangerous Goods

These regulations apply to dangerous commodities transit by rail or road. According to them, all professionals handling hazardous waste must be ADR qualified and have the necessary knowledge to safely transport the trash. The Carriage of Dangerous Goods Regulations is another piece of regulation that influences HCW. This legislation examines the transportation of dangerous commodities and how to manage the risk of spills, which can result in dangerous risks. Health-care practitioners who transport clinical waste to be disposed of must adhere to these laws.

4.7.1.5 The Regulations on Statutory Duty of Care

These regulations establish guidelines for waste management that preserve the environment and human health. They apply to everyone who imports, produces, stores, or disposes of specific types of waste, such as clinical waste. Waste managers have a responsibility to guarantee that the waste they handle does not harm anyone or anything and is appropriately disposed of.

4.7.1.6 The Hazardous Waste Regulations of 2005 (Hazardous Waste Regulations)

In 2005, the Hazardous Waste Regulations went into effect, establishing guidelines for the management and tracking of hazardous waste. It deals with the trash that is regarded to pose a high risk to the environment or human health and hence requires special handling or treatment. Chemicals and solvents are examples of hazardous waste kinds specified in the List of Waste Regulations. The movement of hazardous waste is governed by these laws, which include a documentation system.

4.7.2 Malaysia

In Malaysia, HCW management is overseen to be complied with by the health-care managers subjected to the Environmental Quality Act (EQA) 1974. All guidelines relevant to handling national classification of clinical and related wastes arising from medical, nursing, dental, veterinary, or similar practices are administered by the Department of Environment. In order to exercise the powers conferred by sections 21 and 51 of the EQA 1974, the regulations are cited as Environmental Quality (Scheduled Wastes) Regulations 2005.

4.7.2.1 Environmental Quality Act 1974

Under section 21 [Power to specify conditions of emission, discharge, etc.], the acceptable conditions for any discharge of environmentally hazardous substances, which includes HCW in any area, will be determined by the Minister.

The Minister, after consultation with the Council, may adopt regulations for or with respect to the following requirements under section 51 [Regulations], in addition to and not in derogation of any of the authorities contained in any other provisions of this Act. Some of the requirements are listed here (not in order):

1. prescribing standards or criteria for determining when any matter, action or thing is poisonous, noxious, objectionable, detrimental to health, or within any other description referred to in this Act.
2. prohibiting the discharge, emission, or deposit into the environment of any matter, whether liquid, solid, or gaseous and prohibiting or regulating the use of any specified fuel.
3. prescribing ambient air quality standards and emission standards and specifying the maximum permissible concentrations of any matter that may be present in or discharged into the atmosphere.
4. prescribing ambient water quality standards and discharge standards and specifying the maximum permissible loads that may be discharged by any source into inland waters, with reference either generally or specifically to the body of waters concerned.
5. regulating the establishment of sites for the disposal of solid and liquid wastes on or in the land.
6. Scheduled wastes shall, as far as practicable, before disposal, be rendered innocuous.
7. Generation of scheduled wastes shall be reduced using the best practicable means.
8. Scheduled wastes may be stored, recovered, and treated within the premises of a waste generator.

9. Incineration, disposal, off-site storage, and off-site treatment shall only be carried out at prescribed premises licenced by the DOE.
10. Use of durable waste containers with clear labels. Storage of wastes shall be proper and adequate.

4.7.2.1.1 Environmental Quality (Scheduled Waste) Regulations 2005

There are 15 regulations that must be followed in order to execute the powers granted by sections 21 and 51 of the EQA 1974. Among others, the following subsections are important with respect to HCW:

> (4) Disposal of garbage that has been scheduled.
>
> All scheduled wastes must be disposed of at a specified location and rendered harmless prior to disposal, according to this regulation.
>
> (5) Wastes that have been scheduled for treatment.
>
> The whole content and residual treatment of the scheduled wastes must be carried out in prescribed premises or on-site facilities.
>
> (6) Material or product recovery from scheduled trash.
>
> Any recovery of hazardous health-care waste should take place in designated areas and at on-site recovery facilities.
>
> (7) Implementation of particular waste management procedures.
>
> A request can be made to the Director-General of the Department of Environment Malaysia with a non-refundable charge if the health-care management would like the clinical waste to be managed in a manner other than that specified in the regulation.
>
> (8) The generation of garbage is the responsibility of the individual.
>
> All waste generators are responsible for managing clinical waste in compliance with the Director-General of the Department of Environment Malaysia's recommendations in all aspects of storage, treatment, recovery, packaging, labelling, and transportation at designated locations.
>
> (10) Wastes that are scheduled to be disposed of must be labelled.
>
> (11) The waste generator must retain a record of all scheduled wastes.
>
> (12) Waste generators, contractors, and occupiers of prescribed locations must report information.
>
> (13) Wastes moved outside the grounds of the waste generating must be accompanied with information.
>
> (14) Accidental discharge or spill.

The guidelines include information on how to properly handle and manage HCW from both private and public health-care facilities.

4.7.2.1.2 Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Order 1989

Under this Order, "Land treatment facility" means premises occupied or used for the retrieval of material or product from any scheduled waste that is not produced on those premises; "off-site treatment facility" means premises occupied or used for the processing of any scheduled waste that is not produced on those premises;

Table 4.24 Clinical Waste in the First Schedule, Environmental Quality (Scheduled Wastes) Regulations 2005 [29]

Waste code	Waste that may contain either inorganic or organic constituents
SW 403	Discarded drugs containing psychotropic substances or containing substances that are toxic, harmful, carcinogenic, mutagenic, or teratogenic.
SW 404	Pathogenic wastes, clinical wastes, or quarantined materials.
SW 421	A mixture of scheduled wastes
SW422	A mixture of scheduled and non-scheduled wastes

"scheduled wastes" means any waste that falls into the categories of waste listed in the First Schedule to the Environmental Quality (Scheduled Wastes) Regulations.

According to Section 18 of the EQA 1974, each prescribed establishment must be licenced. The following premises are prescribed as those whose occupation or use by any individual is an offence under the Act unless he is the holder of a licence issued in respect of those premises:

1. Off-site storage facilities, off-site treatment facilities, off-site recovery facilities, and scheduled waste incinerators are all examples of off-site storage facilities.
2. Secure landfills; and land treatment facilities.

4.7.2.1.3 Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Regulations 1989

This regulation provisions concerning the treatment and disposal of HCW, which falls under the scheduled waste category in the First Schedule to the Environmental Quality (Scheduled Wastes) Regulations 1989, now updated as Environmental Quality (Scheduled Wastes) Regulations 2005. Under this First Schedule, the following codes related to clinical waste under this regulation are listed in Table 4.24.

4.8 Covid-19 Situation and Its Impact on HCW Management

Coronavirus disease 2019 (COVID-19) was first found in Wuhan, China, in December 2019 [31] after being spread by the SARS-CoV-2 virus, which produces an acute respiratory disease [32–34]. There is now a Public Health Emergency of International Concern (PHEIC) [35] since the virus has spread to so many countries. Globally, the epidemic remains a severe threat to public health. The rapid rise in the number of people infected with COVID-19 and the disease's high transmission rate has resulted in a large number of hospitalisations. In turn, this has led to a dramatic increase in the amount of health-care-related trash generated. Since the COVID-19 pandemic, the use of personal protective equipment (PPE) has expanded significantly, which has resulted in an increase in HCW [36, 37]. To prevent the virus from

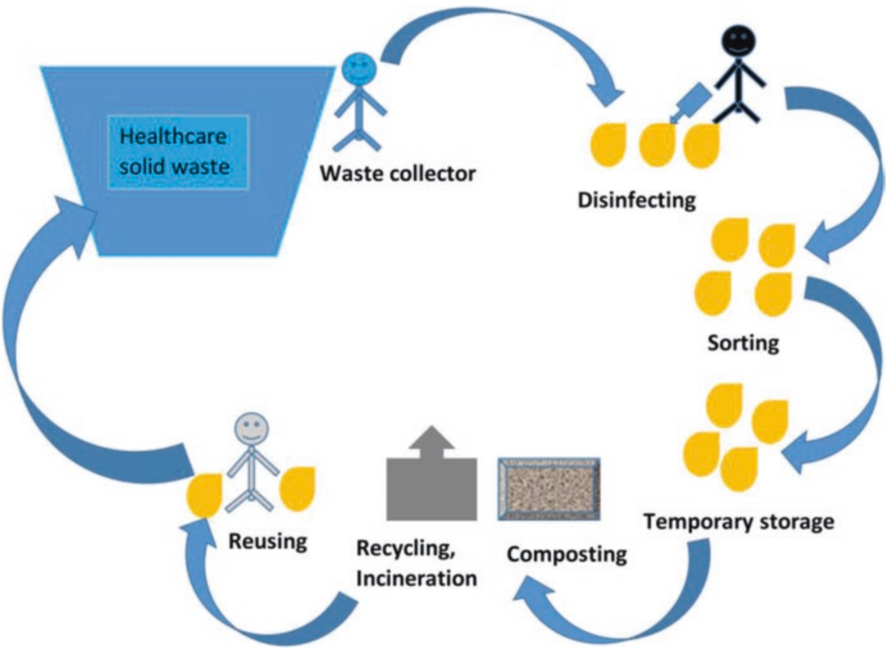

Fig. 4.20 The spread of the COVID-19 virus is aided by the improper treatment of health-care waste [38]

Table 4.25 Details estimated added quantity amount of HCW in each city due to the Covid-19 pandemic [39]

City	Population in a million (World population review)	HCW generated (tonnes/day before Covid-19)	Estimated additional HCW generation (tonnes/day during Covid-19)	Percentage of an increase due to Covid-19
Manila	14	47	280	496
Jakarta	10.6	35	212	506
Bangkok	10.5	35	210	500
Hanoi	8	27	160	493
Kuala Lumpur	7.7	26	154	492

spreading further, it is critical to expand the handling capacity for HCW [34]. Garbage pickers, waste staff, health workers, patients, and the general public are all at danger of infection from harmful microorganisms when the trash is not properly treated (Fig. 4.20). Several countries have put in place safety measures to combat contamination and handle medical waste; however, these are insufficient and vary depending on the environment of the country.

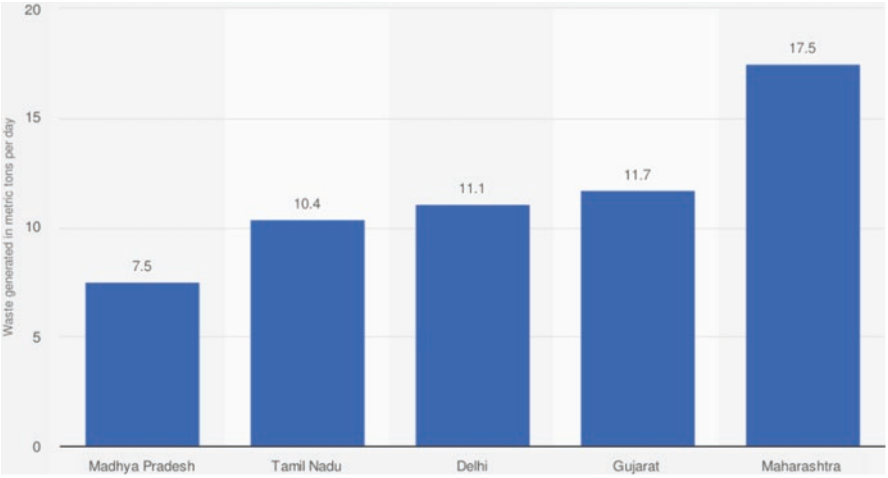

Fig. 4.21 Volume of the coronavirus (COVID-19) biomedical waste generated across India as of July 2020, by state (in metric tonnes/day) [40]

Table 4.25 shows the increased HCW expected in each city as a result of the Covid-19 pandemic [39]. Globally, the COVID-19 epidemic has resulted in an increase in HCW. HCW generation in Bangkok is estimated to have increased to 160 metric tonnes/day during the crisis, up from 26 metric tonnes previously. This was a nearly 500% gain in a single day. The increased usage of disposable personal protective equipment (PPE), such as masks, is one of the reasons for the rapid increase in waste [1].

Figure 4.21 shows the volume of the coronavirus (COVID-19) biomedical waste generated across India as of July 2020 by state (in metric tonnes/day).

The volume of coronavirus (COVID-19) biomedical waste generated in India was 101 metric tonnes/day as of July 2020. With about 17.5 metric tonnes/day, Maharashtra, in the southwest, was the largest producer of medical waste from the epidemic [40]. The most populous cities, including New Delhi, Mumbai, Bangalore, Chennai, and Hyderabad, are the most affected by COVID-19. A substantial amount of COVID-19-related biological waste is generated in India, according to statistics obtained by NDTV [41] on September 18, 2020. (over 100 tonnes/day). About 17% of the total COVID-19-related BMW is attributed to Maharashtra. India's daily trash output has surpassed 850 tonnes. Information on the monthly production of COVID-19-related BMWs in various Indian states may be found in Table 4.26 (from June 2020 to December 2020). Infrastructural and personnel resources in the country aren't sufficient to deal with the influx of BMWs. It was impossible to eliminate the daily 700 tonnes of rubbish with the 198 CBMWFs and 225 captive incinerators that existed. Additional BMW caused havoc with BMW's inventory. BMW management workers are working longer hours in order to meet this demand. From 25 to 349 metric tonnes/day of BMW during the months of May–July, the amount is expected to have doubled during the months of August–October,

Table 4.26 Details on the generation of COVID-19 related BMW in Indian States/UTs from June 2020 to December 2020 [41]

S. No.	States/UTs	Generated BMW (in tonnes)							Total number
		June 2020	July 2020	August 2020	September 2020	October 2020	November 2020	December 2020	
1	Andaman & Nicobar	0.42	INP	INP	0.42	0.434	0.42	0.43	0
2	Andhra Pradesh	165.48	182.81	118.82	112.35	116.095	317.91	328.51	11
3	Arunachal Pradesh	3.36	3.36	3.80	3.36	3.472	3.36	3.47	0
4	Assam	28.38	20.68	12.57	62.61	51.739	50.07	23.41	1
5	Bihar	6.84	20.76	41.54	45.36	44.64	28.08	23.31	4
6	Chandigarh	29.85	5.65	55.34	43.02	73.191	70.83	73.19	1
7	Chhattisgarh	11.19	INP	13.39	9.3	9.61	9.3	9.61	4
8	Daman & Diu	0	INP	0.00	0.48	2.387	1.08	1.15	1
9	Delhi	333.42	389.58	296.14	382.5	365.893	385.47	321.32	2
10	Goa	0.81	0.81	INP	15	7.75	5.43	5.39	0
11	Gujarat	350.79	306.14	360.04	622.89	545.879	423.51	479.57	20
12	Haryana	75.33	184.18	210.69	278.31	238.452	239.4	209.93	11
13	Himachal Pradesh	3.81	12.50	4.94	25.2	28.117	30.03	48.24	2
14	Jammu & Kashmir	10.71	9.77	51.77	57.39	59.303	44.82	35.12	2
15	Jharkhand	INP	INP	2.59	4.8	4.96	4.8	11.63	4
16	Karnataka	84	540.28	588.03	168	218.023	210.99	218.02	26
17	Kerala	141.3	293.32	588.05	494.1	641.979	600.39	542.47	1
18	Lakshadweep	0.3	INP	INP	0.3	0.31	0.3	0.31	0
19	Madhya Pradesh	224.58	5640	106.59	339	308.419	208.65	249.49	13
20	Maharashtra	524.82	1180	1359	524.82	542.314	609	629.30	29

S. No.	States/UTs	Generated BMW (in tonnes)							Total number
		June 2020	July 2020	August 2020	September 2020	October 2020	November 2020	December 2020	
21	Manipur	5.13	0.20	2.09	5.13	5.301	5.13	9.27	1
22	Meghalaya	5.1	1.74	6.34	9.9	12.028	7.65	8.56	2
23	Mizoram	4.2	INP	INP	4.2	3.224	3012	3.22	0
24	Nagaland	3.6	3.4	3.10	2.85	3.317	1.86	2.29	0
25	Odisha	31.86	106.63	109.19	134.01	183.458	222.66	125.58	5
26	Puducherry	18.63	35.82	41.54	63	58.652	28.74	17.11	1
27	Punjab	48	35.59	21.19	234.42	149.606	96.51	86.99	5
28	Rajasthan	177	7.15	50.43	145.08	171.554	141.93	105.93	8
29	Sikkim	6	0.20	0.30	6	4.216	3.69	2.45	0
30	Tamil Nadu	312.3	401.29	481.10	543.78	524.179	300.75	251.22	8
31	Telangana	12.3	10.50	24.04	188.82	144.801	103.89	68.82	11
32	Tripura	0.45	INP	INP	0.45	0.465	0.45	0.47	0
33	Uttarakhand	0.45	0.82	41.45	21.72	108.96	56.76	76.26	2
34	Uttar Pradesh	210	307.54	408.86	507.15	478.082	316.71	276.46	18
35	West Bengal	195	136.37	235.12	434.76	486.793	330.84	279.06	6
Total		3025.41	4253.46	5238.45	5490	5597	4864.53	4527.55	198

Table 4.27 General of coronavirus disease (Covid-19) clinical waste (CW) by country [42]

Country	Amount of waste generated during COVID-19 (kg/bed/day)	Percentage of increase in CW generation Covid-10 pandemic
Taiwan	0.9–2.7	No data
Jordan	3.95	1000%
Wuhan, people's Republic of China	0.6–2.5	213%
Bandung, Indonesia	2.2	17.1%
Penang, Malaysia	0.4–1.0	27%
Thailand	2.9	No data
Mexico	2.0–2.2	No data

according to a Supreme Court report. Segregation at the generation site is currently weak due to a rapid increase in generation, which increases the risk in the generation and increases environmental hazards. In addition, the lack of adequate safety measures for BMW personnel in India is a major problem. Approximately five million sanitation workers (Safai karamchari) are currently cleaning the country and performing their tasks. As a result, they lack adequate personal protection equipment. As a result, the local community is at risk since these workers are in danger. Scientists have found that the virus can survive for up to 72 h on the surfaces of metals and sharps, posing a major risk to workers who regularly gather garbage for more than 24 h. Ragpickers, or karoles, make up a sizable portion of India's population. However, they are not adequately informed or aware of the precautions that must be taken. Over tens of thousands of trash, collectors have fallen victim to the outbreak, with hundreds of them dying as a result.

Agamuthu and Barasarathi [42] have summarised (Table 4.27) data from various sources on coronavirus effects on clinical waste generation in a few countries.

In response to the Covid-19 outbreak, Table 4.28 highlights existing methods for health-care waste separation, storage, and transportation in a number of countries. Table 4.29 describes the handling and disposal of Covid-19 waste in selected countries.

4.9 Conclusion

Increased attention and diligence are needed in the management of health-care waste (HCW) to avoid the health consequences of poor practice, such as exposure to infectious agents and toxic substances. When it comes to waste management, a good HCW management team should have a system that follows a hierarchy that prioritises prevention over disposal. Waste segregation, reuse, and recycling, where applicable, can all be used to reduce the volume of hazardous waste.

Table 4.28 Current practices in selected countries for health-care waste separation, storage, and transportation in response to the Covid-19 epidemic [1]

Country	Practices
Afghanistan	• Separate health-care wastes such as general waste, anatomical waste, and other infectious waste at the point of generation
	• Collect sharps (used auto-disable syringes) separately in yellow boxes
	• Designate a storage area at health-care facilities (separated wastes from each ward are transported by wheeled trolleys)
	• Transport safely packed waste with adequate labelling for off-site treatment and disposal
Bangladesh	• Use separate colour-coded bins (Black: Non-hazardous waste, Red: Sharp waste, Yellow: Infectious/pathological waste, etc.)
	• Store the bins on their premises, to be collected mostly on a daily basis, by separate covered vehicles, for transportation to a treatment site
India	• Use dedicated trolleys and collection bins in COVID-19 isolation wards
	• Waste contaminated with blood/body fluids of COVID-19 patients to be collected in a yellow bag for home quarantined households.
	• Paste a label "COVID-19 Waste" on these items
	• Disinfect with 1% sodium hypochlorite solution daily on (inner and outer) surfaces of containers/bins/trolleys
	• Depute dedicated sanitation workers separately for biomedical waste and general solid waste collection and timely transfer to temporary storage
	• Use a vehicle with GPS and barcoding systems for bag/containers containing HCW for waste tracking, as well as having a label of "Biohazard" or "Cytotoxic" on the vehicle
Indonesia (some local governments)	• Identify the means of classification and communication (symbols, labels)
	• Designate COVID-19 infectious bins
	• Conduct internal sterilisation/disinfection before bags are tied
	• Disinfect bags before collection
	• Label bags "Danger, do not open".
	• Schedule the transportation of waste by the cleaning service every day on weekdays
Japan	• Separate infectious, non-infectious, and general wastes
	• Separate sharps from other infectious wastes with a proper container
	• Seal the container, which is easy to use and hard to break
	• Transport by a designated cart to avoid scattering and spilling wastes within a facility
	• Use short storage periods as much as possible
	• Separate infectious wastes and store them from other wastes in the storage room
	• Access to the storage room only by authorised persons
	• Apply clear labelling, with notification given on bags for infectious wastes at the storage room

(continued)

Table 4.28 (continued)

Country	Practices
Kenya	• Place infectious waste in yellow bins with liners marked "Danger Hazardous Medical"
	• Never sort through contaminated wastes
	• Reuse reusable items only after proper disinfection
	• Tie bags when they are 2/3 full, and disinfect the waste and place it in a designated area for collection
	• Store waste in specified areas with restricted access
Malaysia	• Not separate COVID-19 waste with other infectious waste
	• Equip the cold room in some bigger health-care facilities
	• Collect daily or 3 times a week depending on the quantity
	• Transport only by a special lorry licenced to transport hazardous waste
Mexico	• Same protocol with other infectious waste according to the Mexican Standard #087)
	• Use a container hermetic and polyethylene bag according to the type of health-care wastes
	• Use the bag with translucent red polyethylene of minimum calibre 200 and translucent yellow colour of minimum 300 gauge, waterproof, and with a heavy metal content of not more than one part per million (PPM) and free of chlorine
	• Fill to 80% of the capacity of the bag, and close and transport to the temporary storage site
	• Mark with the universal risk symbol and the legend biological
	• Designate the temporary storage of waste biological-infectious dangerous.
	• Stored biological-infectious hazardous waste separated from the patient areas, and medicine warehouse, etc., accessible for collection and transport without risks of flood and entry of animals, with signs alluding to their dangerousness, access only responsible personnel
	• Not compact hazardous biological-infectious during its collection and transportation
	• Use the collection vehicle with a closed box and hermetic vehicle and operate with cooling systems to keep residues at a maximum temperature of 4 °C (four degrees Celsius) and with mechanised loading and unloading systems
	• Must not be mixed with any other type of municipal or industrial origin during transportation, hazardous biological-infectious waste
Nepal	• Designate waste storage in health facilities (some meet the standard, but some are unmanaged)
	• Use specific trollies for transportation within the hospitals
	• Use specific vehicles for transportation from health-care facilities to treatment WMSPs

(continued)

Table 4.28 (continued)

Country	Practices
South Africa	• Minimise the volume of HCW at source
	• Remove ¾ full sealed box sets, and store at the central storage area prior to collection for treatment and disposal
	• Secure space with the sign of "Suspected COVID-19"
	• Storage on-site in the following manner: sufficient secure capacity, prevent access to these areas to unauthorised persons, mark with warning signs on, or adjacent to, the exterior of entry doors, gates, or lids, secure by use of locks on entry doors, gates, or receptacle lids, and prevent odour
	• Use plastic bags with a capacity of 60 L or more, and at least 80 μm in thickness
	• Ensure that the time between collection of a consignment by transporter from the relevant generator's premises and the treatment of that health-care risk waste does not exceed 72 h if pathological waste is unrefrigerated
Thailand (Chiang Rai)	• Separate into two types: (1) sharp items; (2) non-sharp items (COVID-19 waste under the non-sharp items)
	• Disinfect and double bags
	• Designate a specific storage area
	• Send waste from community health-care facilities to district health-care facilities once a week
	• Temperature-controlled storage available at the district level
	• Transport by licensed WMSPs (require temperature-controlled vehicle)
	• Treat within 48 h after being transported
	• Disinfect vehicles and bins daily with NaClO

Table 4.29 Covid-19 waste treatment and disposal in selected countries [1]

Country/city	Covid-19 waste generated from a health-care facility	Covid-19 waste generated from household/ quarantine location
Bangladesh	• Incinerator	• N/A
India	• Common biomedical waste treatment facility (CBWTF)	• Hand over to waste collector identified by urban localities or as per the prevailing local method of disposing of general solid waste.
	• Permit disposal by deep burial only in rural or remote areas without CBTWF facilities	• Urban local body (ULB) shall engage CBWTF operator for the ultimate disposal of biomedical waste collected from quarantine home/home care of waste deposition centres or from doorsteps as may be required depending on the local situation. ULB shall make an agreement with CBWTF in this regard.
	• In case of generation of a large volume of yellow colour coded (incinerable) Covid-19 waste beyond the capacity of existing CBWTF and the captive BMW incinerators, permit HW incinerators at existing treatment, storage, and disposal facilities (TSDFs) or captive industrial incinerators if any exist in the State/Union territory. In such case, ensure separate arrangements for handling and waste feeding	

Table 4.29 (continued)

Country/city	Covid-19 waste generated from a health-care facility	Covid-19 waste generated from household/ quarantine location
Indonesia (some local governments)	• Mostly incineration, disinfect at source and transport to the disposal sites or open burning (if no incinerator), hazardous waste landfill	• Directly burn easily at home • Collect and transport by office staff to the cement factory incinerator for the burning process (Padang)
Japan	• Incineration, melting, steam sterilisation (autoclave) followed by shredding, dry sterilisation followed by shredding, disinfection followed by shredding and disposing of the specific sanitary landfill	• Mix recyclable items with other combustible waste (and incinerate) • Discharge incombustible waste after 7-day storage at source
Kenya	• Incineration, microwave, crude dumping of ash and microwaved end-product at the municipal dumpsite	• N/A
Malaysia	• Mostly incineration	• Transport all ash from the incineration plants to the hazardous waste treatment centre and solidify with cement to be disposed of in a special landfill
Mexico	• Treat and dispose of as normal hazardous HCW (autoclave, incinerator, radio wave, etc.)	• Incinerated or confined in an emergency cell in a landfill and earth covered every day
Nepal	• Mostly buried, small-scale incineration, or dumped backyard, municipal landfill, or other areas	• N/A
Saint Lucia	• Steam sterilisation, autoclave, chemical disinfection (some)	• N/A
South Africa	• Incineration, non-burn technologies (autoclaves, converter, microwave)	• Covid-19 waste generated in a household is managed as part of municipal waste • Waste generated at a quarantine facility is treated as HCW, and most are treated at incineration or non-burn treatment facility
Sri Lanka	• Incinerator	
Thailand (Chiang Rai)	• Incinerator, autoclave, waste management service provider (WMSP), sanitary landfill	• N/A

It is critical that all waste workers, including municipal employees, wear personal protection equipment (PPE) and practise proper hand hygiene when handling hazardous materials (HCW). From a sustainability perspective, it is important to consider the informal sector (which typically plays a significant role in waste management). For health-care facilities and those in the informal sector, such as waste collectors, HCW management training and awareness-raising are critical. In order to continually improve HCW management, stakeholders should engage in regular discussions to exchange ideas, statistics, and information, as well as lessons learned. Rapid response is also possible in an emergency.

Medical waste incineration is the most applied treatment of hazardous HCWs, together with autoclaving and microwaving, steam treatment integrated with internal mixing and chemical treatments. All countries should implement a comprehensive system that addresses responsibilities, resource allocation, handling, and disposal in tandem with strong political will. Progress will be gradual and sustained by raising awareness of the risks associated with HCW and of safe practices; and ensuring that people are protected from hazards when collecting or handling waste, transporting or storing it. For the long-term, universal improvement, government support and commitment are required, but immediate local action can be taken to improve conditions.

All countries should refer to international guidelines for safe HCW management, which should be made available to the general public. Covid-19 has taught a good lesson to the world on how important it is to be pre-prepared with appropriate protocols in managing and controlling not only the infection but also handling all health aspects, including the HCW management. HCW general ideas and criteria for limiting infectious waste should be followed during the future pandemic.

Glossary

ADR ADR is an abbreviation for "Accord européen relatif au transport international des marchandises dangereuses par route", which translates as "The European Agreement concerning the International Carriage of Dangerous Goods by Road". The international term ADR has been so widely used in the transport industry that almost anyone in the industry understands what is meant, regardless of their country of origin.

Best Environmental Practices (BEP) Best Environmental Practice (BEP) means the application of the most appropriate combination of environmental control measures and strategies.

Common biomedical Waste Treatment Facility (CBWTF) A Common Biomedical Waste Treatment Facility (CBWTF) is a set-up where biomedical waste, generated from a number of health-care units, is imparted necessary treatment to reduce adverse effects that this waste may pose. The treated waste may finally be sent for disposal in a landfill or for recycling purposes.

Genotoxic Waste Genotoxic wastes are a subset of hazardous waste that may have mutagenic, teratogenic, or carcinogenic properties. This kind of wastes include residues of certain cytostatic drugs or vomit, urine and faeces from patients treated with cytostatic drugs, chemicals and radioactive material.

Half-Life The time taken for the radioactivity of a specified isotope to fall to half its original value. For example, "iodine-131 has a half-life of 8.1 days".

Personal Protective Equipment (PPE) Personal Protective Equipment (PPE) is equipment that will protect the user against health or safety risks at work. It can include items such as safety helmets, gloves, eye protection, high-visibility clothing, safety footwear, and safety harnesses. It also includes respiratory protective equipment (RPE). The hazards addressed by protective equipment include physical, electrical, heat, chemicals, biohazards, and airborne particulate matter.

Public Health Emergency of International Concern (PHEIC) A Public Health Emergency of International Concern (PHEIC) is a formal declaration by the World Health Organization (WHO) of "an extraordinary event which is determined to constitute a public health risk to other States through the international spread of disease and to potentially require a coordinated international response", formulated when a situation arises that is "serious, sudden, unusual, or unexpected", which "carries implications for public health beyond the affected state's national border" and "may require immediate international action".

Puskesmas Puskesmas (Indonesian: Pusat Kesehatan Masyarakat, English: Community Health Centre) are government-mandated community health clinics located across Indonesia. They are overseen by the Indonesian Ministry of Health and provide health-care for the population on the sub-district level.

Regulated Medical Waste (RMW) Regulated Medical Waste (RMW)—also known as "biohazardous" or "infectious medical" waste—refers to wastes that contain blood, body fluids, or other potentially infectious materials like sharps, as a result posing a risk of transmitting infection.

SARS-CoV-2 Virus Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) is the coronavirus that causes COVID-19 (coronavirus disease 2019), the respiratory illness responsible for the ongoing COVID-19 pandemic. The virus previously had a provisional name, 2019 novel coronavirus (2019-nCoV), and has also been called human coronavirus 2019 (HCoV-19 or hCoV-19). First identified in the city of Wuhan, Hubei, China, the World Health Organization declared the outbreak a Public Health Emergency of International Concern on 30 January 2020 and a pandemic on 11 March 2020. SARS-CoV-2 is a positive-sense single-stranded RNA virus [14] that is contagious in humans. As described by the US National Institutes of Health, it is the successor to SARS-CoV-1, the virus that caused the 2002–2004 SARS outbreak.

Stockholm Convention's BAT Under the Stockholm Convention, Best Available Techniques (BAT) are defined as "the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for release limitations designed to prevent and, where that is not practicable, generally to reduce releases of chemicals listed in Part I of Annex C and their impact on the environment as a whole".

UNDP, United Nations Development Programme The United Nations Development Programme (UNDP) is a United Nations organisation tasked with helping countries eliminate poverty and achieve sustainable economic growth and human development. Headquartered in New York City, it is the largest UN development aid agency, with offices in 170 countries.

WHO, World Health Organization World Health Organization (WHO) is the United Nations agency founded in 1948 that connects nations, partners, and people to promote health, keep the world safe, and serve the vulnerable—so everyone, everywhere can attain the highest level of health.

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Chapter 5
Energy Recovery from Solid Waste

Rosnani Alkarimiah, Muaz Mohd Zaini Makhtar, Hamidi Abdul Aziz, P. Aarne Vesilind, Lawrence K. Wang, and Yung-Tse Hung

Abstract The growing amount of solid waste (SW) and the related waste disposal problems urge the development of a more sustainable waste management practice. The organic wastes that are generated include food scraps, yard debris, paper, wood, and textile byproducts. According to most studies, almost all landfill gas is created by the breakdown of organic waste in combination with the naturally occurring bacteria in the soil that is used to cover the landfill. They are inevitably linked to the treatment and disposal of solid waste. In this instance, treatment is utilized to restore or recover important materials or energy, control waste generation, or manage trash

R. Alkarimiah (✉)
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: cerosnani@usm.my

M. M. Z. Makhtar
Bioprocess Technology, School of Technology Industry, Universiti Sains Malaysia, Minden, Pulau Pinang, Malaysia
e-mail: muazzaini@usm.my

H. A. Aziz
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Solid Waste Management Cluster, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: cehamidi@usm.my

P. A. Vesilind
Engineering, Department of Civil and Environmental Engineering, Bucknell University, Lewisburg, PA, USA

L. K. Wang
Lenox Institute of Water Technology, Latham, NY, USA

Y.-T. Hung
Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, OH, USA
e-mail: y.hung@csuohio.edu

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disposal before it is deposited or discarded in landfills. A disposal site where solid trash, such as paper, glass, and metal, is buried between layers of dirt and other materials, such that land around the site is less contaminated. Waste-to-Energy (WtE) technologies are being developed globally. The essential concepts of available technologies and several specific technologies' processes are summarized. Technologically sophisticated processes (e.g., plasma gasification) gain increased attention, with an emphasis on energy and material recovery potential. This chapter ends with a comparison of the various technologies, highlighting variables impacting their application and operational suitability. More budgetary allocation for technical support by the government is also recommended in this chapter. This will help to promote solid waste management by reducing, reusing, and recycling waste. It will also help to retain employees by providing a good wage, benefits, and training. As a result, WtE technologies have the potential to make a significant contribution to the growth of renewable energy while also reducing landfilling expenses and the associated environmental implications. However, deciding between the two options necessitates further financial, technological, and environmental examination using a life cycle assessment (LCA) methodology.

Keywords Waste-to-energy (WtE) · Waste reduction · Landfill · Refuse-derived fuel · Renewable energy · WtE technologies

Acronyms

ASTM	American Society for Testing and Materials
C&D	Construction and demolition
C&I	Commercial and industrial waste
CBM	Carbohydrate binding module
CD	Catalytic domain
CHP	Combined heat and power
CO_2	Carbon dioxide
EAP	Environmental Action Plan
EG	Endo-cellulase
FiT	Feed-in tariff
GHG	Greenhouse gas
HDI	Human development index
HMF	Hydroxymethyl furfural
IL	Ionic liquids
LCA	Life Cycle Assessment
MBT	Mechanical Biological Treatment
MSW	Municipal solid waste
NEM	Net energy metering
PV	Photovoltaic

RDF	Refuse-derived fuel
REC	Renewable Energy Consumption
SRF	Solid recovered fuel
SW	Solid waste
WtB	Waste-to-bioproducts
WtE	Waste-to-energy

5.1 Energy Recovery: Introduction

Waste management is essential for urban infrastructure since it protects the environment as well as human health. This is a significant political dilemma as well as a technological, environmental issue. Waste management is inextricably linked to a variety of problems, including urban patterns, resource use rates, employment and income levels, and other socioeconomic and cultural determinants. Preventing and eliminating waste benefits the environment, public health, and protection, as well as the economy. Adhering to the "less is enough" philosophy protects human health and safety by minimizing exposure, thus reducing the need for environmental disposal. As a result, recycling costs are lowered because there is less waste.

The industrial revolution ushered in the age of automation, in which machines operated autonomously of human labor. Then there is the fact that energy demand has increased dramatically, and men are increasingly seeking energy capabilities. Power is inversely proportional to the Human Development Index (HDI). The energy consumption per capita is a proxy for HDI. Most energy sources have been extracted for a long time from fossil fuels such as coal, oil, and other sources. These fossil fuels, however, have substantial reserve limits. Furthermore, these fuels emit greenhouse gases (GHGs) and cause other important global environmental impacts, collectively known as global warming. At the same time, as human society has grown, energy demand has increased exponentially. Humans began moving energy from one type to another as technology advanced.

Solid waste management is the efficient organization of activities involved in the collection, separation, storage, transportation, transfer, processing, treatment, and disposal of solid waste. Solid waste management objectives are to control, collect, use, handle, and dispose of solid waste in the most cost-effective manner possible while adhering to applicable national laws and regulations. Waste is produced in and from various sectors; residential, commercial, manufacturing, and other waste generated from these sources is highly heterogeneous and exhibits a range of physical characteristics. The heterogeneity of waste produced is a significant impediment to its use as a raw material.

Climate change happens naturally and has done so many times in the Earth's history. However, over the last two centuries, climate change has arisen because of industrialization and human behavior. Currently, the atmosphere is exceptionally conducive for human life, but with the increased pace of climate change, we could be moving toward a less hospitable environment for humans. It is agreed that this can occur naturally over time and that we can adapt. However, as the abuse of fossil fuels and natural resources accelerates the pace of climate change, we will be unable to respond quickly enough or with sufficient resources.

The recent stages of waste generation must be reduced, and material and energy recovery must be increased, as these are considered necessary measures toward an environmentally sustainable waste management system. Primarily, incinerators were used to diminish waste mass all over the world, but incinerators are now being used to recycle energy. The extracted biogas from the landfill is used to generate electricity and heat. Material recycling and food waste composting are the most relevant systems from the standpoint of the public [1].

The issues caused by solid waste can be tackled by using cutting-edge technologies. There are numerous waste-to-energy (WtE) technologies available today that efficiently recover and use energy, including anaerobic digestion (i.e., solid-state anaerobic digestion), thermal conversions such as pyrolysis/gasification and thermochemical conversion (i.e., bioreactor landfill). Every piece of equipment is specifically designed for the composition and volume of solid waste [2]. Without verifying the magnitude and structure of waste produced, it appears challenging to suggest appropriate waste management plans and technologies [3]. The composition of solid waste is critical when constructing a solid waste management system. Recycling, composting, landfilling, and all other waste-to-energy technology solutions can be included in this management scheme. The components of the waste stream influence the type of energy recovery equipment used. As a result, the technological and economic feasibility of a particular waste-to-energy scheme is determined by waste stream characteristics.

For the period 1970s and early 1980s, a lot of countries around the world were severely impacted by the excessive expenditure of trade in oil and the shortage of low-expenditure substitute oils. This situation triggered a quest for alternative energy sources, which rekindled interest in municipal waste as one potential source. There were two reasons why the enhanced fascination in the energy capability of urban waste was inexplicable: (a) a significant proportion of the waste could consist of fuel components, i.e., materials which could be used for heat generation; and (b) incineration of municipal waste, dependent on country, and exploitation of the waste heating generated in Europe.

Numerous combustible elements of municipal solid waste are also recyclable, and therefore able to use as a substrate for biological transformation to a fuel gas that can be distorted directly to the energy (i.e., direct conversion to heat energy) or able to stockpile or transferred for subsequent conversion (i.e., implicit conversion). The energy potential for urban waste is different both in terms of energy content and ease of "extraction." Many different methods exist for extracting energy from solid waste. Figure 5.1 illustrates a graphical diagram of the various energy recovery processes, as well as the different forms of fuel and energy sources that can be extracted from municipal wastes. As exemplified in the diagram, energy recovery can be undertaken by or deprived of automated, manual, or mechanical/manual waste handling preceding to conversion (i.e., pre-processing). Without

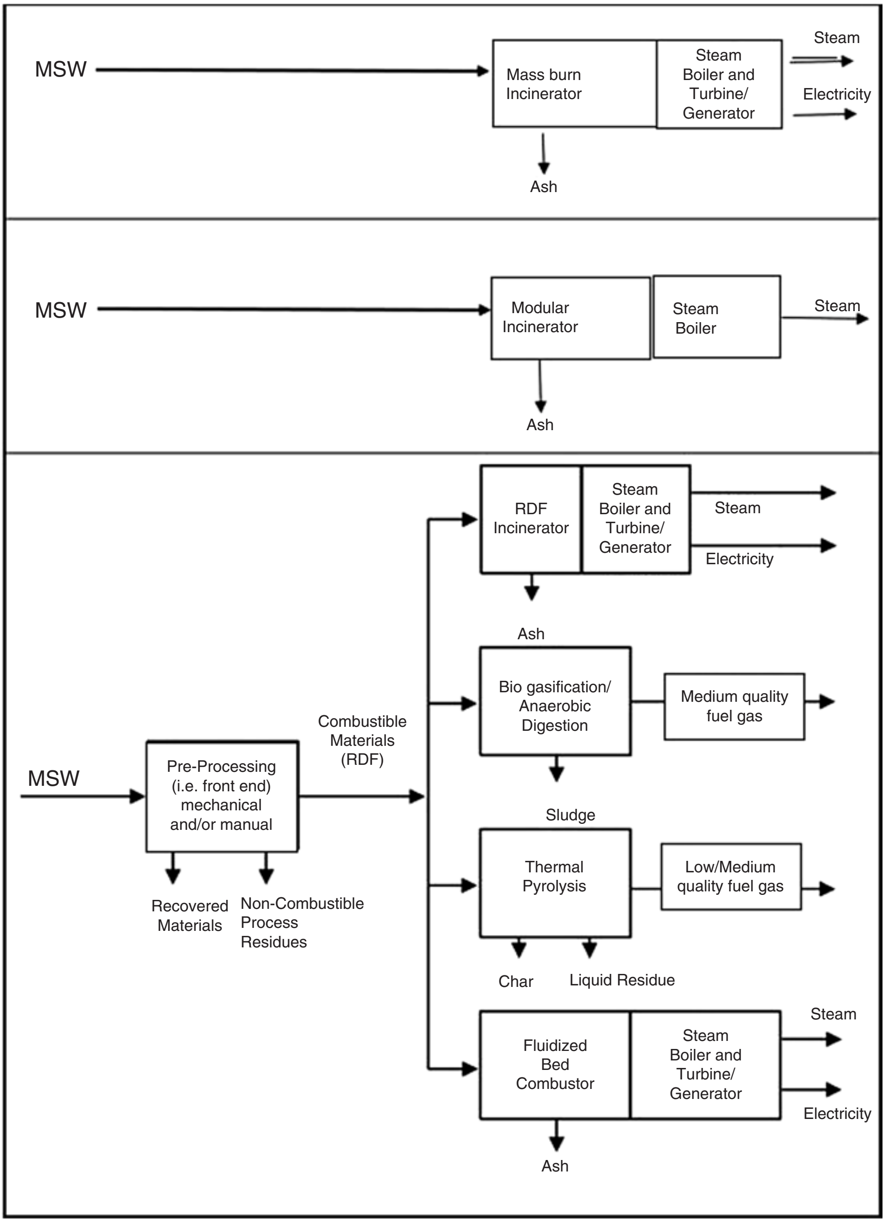


Fig. 5.1 Techniques of recovering energy from solid wastes [4]

pre-processing, energy recovery is achieved mainly by transforming waste into the form in which it was generated. Pre-processing is used to recover energy using one or more of the methods depicted in the diagram. The primary purpose of waste pre-handling for energy recovery is to isolate the organic from non-inflammable and inflammable fractions from the remainder of the waste.

There were no sanitary control schemes in place prior to 1800. Garbage was burned or dumped in alleys, streets, and rivers [5]. As the 1800s approached, several families dug disposal pits as a substitute. Animals, both wild and domestic, were used for waste disposal in the 1800s. Cholera and yellow fever epidemics prompted local governments to improve sewage treatment and water sources by the end of the 1800s. Instead of developing an integrated waste management system after WWI, contractors for waste management were outsourced. Multiple transfer stations were built to serve small household units after a common disposal site was found. During the 1930s and 1940s, the federal government imposed location limits, preferring dumpsites to be built away from waterways.

Both traditional solid waste management efforts and new solid waste management efforts aim to avoid disease transmission. Due to the individual household emphasis, traditional efforts were simplistic and disjointed. Furthermore, no consideration was given to the effects on the climate. They were created based on a lack of understanding of the connection between waste and disease. The new initiatives, on the other hand, are incorporated and planned with the general interests of public health and environmental protection in mind. The current efforts begin with the generation of waste and end with its disposal [5]. The existing efforts necessitate a continuous monitoring system as well as a spill prevention system. Traditional approaches focused solely on the protection of surface waterways.

According to the United Nations Environmental Program in 2012, there is a large potential for energy recovery from solid waste based on continuously developing urban waste management systems and a rise in waste-to-energy investors to the tune of $1 billion [6]. Furthermore, compared to other sources of energy, waste-derived energy is simple to generate and inexpensive and would be a welcome alternative during these difficult economic times.

The composition of the wastes determines the fuel benefit of refuse-derived fuel, as well as the actual incineration of the material. The comparatively high moisture content of putrefiable materials, for example, must be diminished before ignition can occur. The energy required to remove the wastes must either come from the energy released when dry raw material is burned, or it must be supplied by combusting supplementary (e.g., fossil) fuels alongside the wastes. Agreeing to the statistics in Table 5.1, the municipal wastes produced in numerous developing countries can be putrefiable to the tune of 50–70% on a wet weight basis. The volumes of discarded paper and plastics, on the other hand, are comparatively small.

The low amount of flammable material means that the relative fraction of dry, combustible materials is minimal. Not only that, in certain developed countries, but the percentage of total urban garbage also made up of ash is quite significant (e.g., up to 60% where wood ash, coal ash, or both are major waste byproducts of domestic activities). Together, these features of waste will result in the creation of a system that uses energy, rather than one that provides it. It may not be reasonable for underdeveloped nations or may be only feasible in a limited number of locations or conditions.

Table 5.1 Difference of solid waste description worldwide (% wet wt) [4]

Location	Putrescibles	Paper	Metals	Glass	Plastics, rubber, leather	Textiles	Ceramics, dust, stones	wt (g)/capita/day
Bangalore, India	75.2	1.5	0.1	0.2	0.9	3.1	19.0	400
Manila, Philippines	45.5	14.5	4.9	2.7	8.6	1.3	27.5	400
Asunción, Paraguay	60.8	12.2	2.3	4.6	4.4	2.5	13.2	460
Seoul, Korea	22.3	16.2	4.1	10.6	9.6	3.8	33.4	2000
Vienna, Austria	23.3	33.6	3.7	10.4	7.0	3.1	18.9	1180
Mexico City, Mexico	59.8	11.9	1.1	3.3	3.5	0.4	20.0	680
Paris, France	16.3	40.9	3.2	9.4	8.4	4.4	17.4	1430
Australia	23.6	39.1	6.6	10.2	9.9		9.0	1870
Sunnyvale, California, USA	39.4	40.8	3.5	4.4	9.6	1.0	1.3	2000
Bexar County, Texas, USA	43.8	34.0	4.3	5.5	7.5	2.0	2.9	1816

5.2 Energy Recovery Context

"Waste-to-energy" or "energy-from-waste" (often abbreviated to WtE) is a blanket term that covers a wide range of thermal treatment techniques and technologies. It's a technique for recovering energy (in the form of heat) from waste combustion and turning it into electricity. This energy is either returned to the National Grid or local heat and power networks, or it is used to deliver both electricity and heat (combined heat and power (CHP)) to nearby communities or industries.

Alternatively, waste might be the residue left after recyclables have been removed from a general waste stream, or it can be a refuse-derived fuel (RDF) or solid recovered fuel (SRF) generated at a Mechanical Biological Treatment (MBT) plant. Biodegradable and non-biodegradable materials are used to make RDF, which has a lower and less predictable calorific value than SRF. RDF is made from these materials. SRF is designed for industrial processes such as cement kilns and power plant furnaces and is made to a specific standard such as that issued by the European Committee for Standardization.

For example, in the United Kingdom, energy from waste has endured from a scarcity of public trust and acceptance due to early low-quality waste incinerators, which were mostly disposal-only plants that burned waste to minimize its volume. The adoption of modern WtE treatment has also been sluggish, owing to the 1970s' preponderance of landfills. Today, a significant driver is the Waste Framework Directive's statutory-backed waste hierarchy. This places a premium on waste management with the aim of preventing, reusing, and recycling it; therefore, obtaining energy from waste should be reserved for genuinely remaining waste unable to achieve by these approaches.

Incineration, waste-derived fuel combustion, and more advanced technologies like pyrolysis and gasification are examples of available methods (producing fuel gas from the waste by heating either a zero or low-oxygen environment). Thermal treatment alone does not account for all the environmental advantages; energy conversion equipment utilized in conjunction with it does. Furthermore, the process' overall efficiency will be influenced by the amount of energy required to run it.

In 2013, the UK's first commercial-scale gasification plant started operations, with the capacity to generate 6 MW of electricity. By 2020, waste-derived renewable electricity from thermal combustion in England is projected to increase from 1.2 TWh to between 3.1 and 3.6 TWh, depending on how much of the solid recovered fuel generated in the UK is used. Table 5.2 summarizes the common technologies and associated efficiencies for WtE systems.

Waste management is a vital aspect of the urban system because it guarantees environmental and human health security. It is a highly political concern as well as a technical, environmental issue. Waste management is inextricably linked to several issues, including urban lifestyles, resource use patterns, jobs and income levels, and other socioeconomic and cultural considerations. Waste hindrance and minimization have beneficial effects on the climate, human health and safety, and the economy. By minimizing exposures and reducing the demand for disposal on the environment, the "less is better" principle offers good quality safeguard of human health and safety. The cost of disposal is also reduced as the amount of waste generated decreases.

Increased living levels and high rates of resource use have had an unintended and detrimental impact on the urban environment, resulting in the production of wastes well beyond the ability of local governments and agencies to manage. Cities are currently dealing with issues such as high waste levels, associated costs, waste management processes and methodologies, and waste effects on the local and global climate.

However, these concerns have initiated a window of opportunity for cities to pursue alternatives involving the government and the private sector, new technology and disposal practices, as well as behavioral improvements and public awareness.

Table 5.2 Regular instruments and proficiencies for WtE systems [7]

	Proficiency
Conventional technologies	
Direct combustion (incineration of dry biomass)	15–27%
Combustion of waste-derive fuel	25%
CHP	40%
Advanced thermal treatments	
Gasification	Up to 30%
Pyrolysis	Up to 30%

Many cities around the world have successfully addressed these problems, as shown by good practices.

There is a need for a full rethinking of the concept of "waste"—to determine if waste is waste. A rethinking that entails the following:

1. WASTE to become PROSPERITY
2. REFUSE to become RESOURCE
3. TRASH to become CASH

There is a strong need to move away from the existing waste disposal strategy, which focuses on communities and uses high energy/high technology resources, and toward waste handling and waste reusing (which includes public-private partnerships, aims for ultimate waste minimization—driven at the community level, and uses low energy/low technology resources). Increased community involvement, recognizing economic benefits/waste recovery, focusing on life cycles (rather than end-of-pipe solutions), decentralized waste administration, mitigating environmental impacts, and integration outlay costs with long-term goals would all be defining criteria for future waste minimization initiatives.

The repurposing of "waste" products is referred to as resource recovery. It entails gathering, sorting, and processing materials that are historically regarded as waste and converting them into raw materials for the creation of new items. Recycling and composting are two of the most well-known methods for resource recovery.

The process of reclaiming materials that were previously believed to be unusable is known as resource recovery. It is not waste management, which is the industry norm for most garbage companies. Traditional waste collection and transportation firms collect and transport waste to large-scale, single-use facilities such as landfills or incinerators. Unlike waste management, resource recovery acknowledges that such resources also have value. Via our innovative projects, services, and technology, ecology makes it easier to extract the remaining value of these resources. The waste hierarchy of waste reclamation is depicted in Fig. 5.2.

The aim of resource recovery is to maximize the usefulness of all resources while landfilling only those that are no longer useful. Over time, we anticipate that the volume of landfill-bound waste will decrease to a marginal level because of our resource recovery efforts. Recovery of resources is important for environmental sustainability. Food scraps, yard trimmings, recycled paper, plastic, and fabrics are

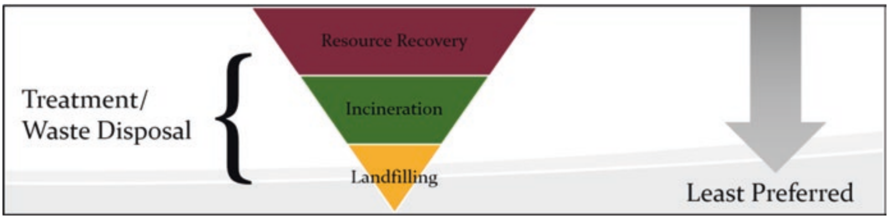


Fig. 5.2 Waste hierarchy

recovered for reuse, thus avoiding the use of new materials. These are only a few examples of recycled products that support global agriculture and manufacturing.

Because the Waste-to-Energy process is irreversible, the decision to reuse urban wastes for the primary goal of energy recovery has an impact on ecological resource utilization. On the one side, recovering the waste's calorific value and reaping the associated benefits could be preferable to losing the waste's energy recovery capacity to landfill disposal. Irreversible energy usage, on the other hand, can overlook more sustainable resource uses of that material, such as reuse, recycling, or reclaiming for substantial intrinsic recovery and higher exemplified energy value.

Energy processing, also known as energy recovery, is a broad term that refers to a variety of technologies and processes that convert the material being treated into a fuel that can be used to generate electricity, steam, or heat. The term "energy recovery" has traditionally been correlated with waste management technologies, and it refers to a variety of processes, including landfill gas generation, biogas generation from organic waste, thermolysis, and feedstock recycling for fuel production and incineration. The core principles of this technology are widely considered to be the most widely used technique for waste-to-energy conversion. Furthermore, incineration units are usually the most widely used waste management system and the most effective treatment for plastics. The vital governing parameters of incineration units are defined in detail, as well as feedstock characteristics and incineration applicability. It illustrates the different types of incineration units used in waste management that can be used to handle municipal and plastic solid waste.

5.2.1 Recycling and Energy from Waste

Energy technologists have been focusing on environmentally friendly processes that can turn waste materials into usable energy because of the quest for renewable and alternative energy sources. Waste-to-Energy (WtE) technologies take advantage of urban waste's abundance to produce electrical and heat energy, which is accomplished through a variety of complicated conversion methods. Municipal waste, unlike fossil fuels, is considered a renewable energy source because it is made up of many biological materials that are part of regular life in a municipality [8]. The accretion of organic waste can be due to population shifts toward urban areas. As a result, WtE facilities in the country are in desperate need of growth.

The first waste-to-energy (WtE) incinerator was installed in Nottingham, United Kingdom, in the late nineteenth century. The procedure entailed the burning of organic materials with the recovery of energy as a result. Pyrolysis/gasification, refuse-derived fuel (RDF), plasma arc gasification, incineration, trans-esterification, and anaerobic digestion are the six major WtE technologies currently in use around the world. WTE technology selection is inspired by a variety of considerations, involving quality, waste type, geographic location, and labor ability requirements [9].

The provision and enhancement of required infrastructure and services continue to outpace the growth of urban areas. As a result, waste management issues have arisen, as most municipal governments face significant financial constraints, limiting their ability to provide efficient waste disposal. Owing to a lack of comprehensive waste management strategies, all towns, cities, and development points face the problem of littering, waste dumping, and inappropriate waste disposal. Many people in the world today are realizing that what some have discarded as waste has meaning. Communities in many developing countries, for example, make a living by aggregating waste plastics, wastepaper, and cardboard boxes, to name a few.

Even though the world produces 4 billion tonnes of all types of waste every year, only a quarter of that waste is recycled or reused. Although there are valuable items like cardboard, plastics, glass, and metals in municipal solid waste (up to 50% in developing countries), most waste is sent to landfills. Given the low prices of recycling products on the global market, recycling and waste claims have been barely profitable. Recycling is the process of converting a commodity or resource that has attained the end of its valuable life into usable raw material for the creation of a new product. Waste recycling is defined as the method of reclaiming material that would otherwise be discarded as waste. It is a technique for recovering resources.

As a result, the new waste management trend is to view waste as a resource to be utilized rather than a nuisance to be treated and disposed of. The material could be removed and recycled, or it could be turned into something else. Secondary resource recovery, recycling, and other terminology are used to describe the method of removing resources or value from waste. Waste disposal is being increasingly recognized as unsustainable in the long run due to the finite availability of most raw materials. Waste reuse is a type of recycling that refers to reusing anything that would otherwise be discarded without any transformation processes. Wastepaper is an excellent example of reused waste. Newspapers, magazines, and books, as well as cardboard and mixed sheets, are examples of wastepaper.

Thormak [10] described recycling potential as the environmental impact of a material's output, with recycled material serving as a replacement for less environmental impact from recycling processes and associated transportation. The recycling potential can thus be briefly described as the amount of embodied energy and natural resources that can be saved by reuse and recycling. According to a study by, waste policies must be viewed in the context of the wider life cycle, which includes resource use and development, as well as waste reduction and recycling. Prevention and recycling of other thin materials, as well as energy recovery and pretreatment, are both options for diverting waste from landfills. The management problem has become an increasing issue for national governments, local governments, environmentalists, academics, and the public.

The value of recycling wastes has been recognized in surveys conducted by the United States government and other non-government organizations in the region. The standards for safe waste recycling, on the other hand, have not been standardized. According to studies, the USA recycles between 7% and 15% of its waste. If recycling is done correctly, it can eliminate waste or garbage issues. Many NGOs

(Non-Governmental Organizations) and private sector companies have taken the initiative to segregate and recycle waste at the community level.

Classification findings are a method of determining the criterion structure of a waste stream for a specific area, which is then followed by sampling and sorting procedures. These studies are beneficial for creating assessments about waste management policies and ensuring accountability to taxpayers. Classification implies the approach of sorting a waste stream based on the handling proposed for the waste stream. Various processing systems are used or have the potential to be used in waste management activities, ranging from treatment and recycling to recovery and utilization; the applications used are determined by the needs and priorities of a specific prerogative. Table 5.3 outlines waste management collection systems and their purposes.

To manage the sampling, sorting, and analysis of their MSW sources, numerous provinces use a description by the ASTM International standard D5231-92 [12]. The sampling procedure, which defines the minimum sample size and number of samples to collect to achieve a representative sample of the population, is more widely used. Individual jurisdictions are free to change and customize the list to meet the needs of their premeditated sample, with a minimum suggested number of sorting categories of 13 (Table 5.4).

Several characterization studies are performed to thoroughly examine the content of the MSW flow and the source (demographic sampling analysis), which allows assumption as to the need of dealing with waste management plans. The

Table 5.3 Handling methods for urban solid waste [11]

Handling methods	Rationale
Physical	
Sorting	Material recovery
Recycling	Waste reduction/recovery waste treatment
Size reduction	
Chemical	
Catalytic conversion/partial oxidation	Carbon recycling Waste utilization
Pyrolysis (energy recovery)	
Biological	
Composting	Waste utilization/recovery waste utilization
Anaerobic digestion (energy recovery)	Waste utilization
Ethanol fermentation	
Thermal	
Incineration	Waste disposal/treatment waste utilization
Combustion (energy recovery)	Waste treatment/utilization
Pyrolysis (energy recovery)	Waste utilization
Gasification (energy recovery)	
Landfill	
Landfilling	Waste disposal gas recovery
Landfill gas recovery	

Table 5.4 Suggested element groups for classifying MSW [12]

	Categories	
Mixed paper	Plastic	Ferrous
High-grade paper	Yard waste	Aluminum
Newsprint	Food waste	Glass
Corrugated cardboard	Wood	Other inorganics
	Other organics	

organization of MSW classification methodologies is also driven by composition studies. Once an effective classification framework has been developed, characterization will help determine the viability of processing technologies based on waste composition. Non-putrescible organic matter, for example, may be used in gasification waste-to-energy processes; however, a greater substance of inert materials would decrease the process's performance.

5.2.2 Waste-to-Energy Classification

Various waste produced enter land and water bodies without proper treatment, which leads to substantial water pollution. They also contribute to air pollution by emitting greenhouse gases such as methane and carbon dioxide. Any organic waste from urban and rural areas and plants is a resource because of its capability to degrade and produce electricity.

The obstacles initiated by solid and liquid wastes can be significantly diminished by employing environmentally friendly waste-to-energy technologies that enable waste to be treated and processed before disposal. These initiatives will lessen the volume of waste generated, create a significant amount of energy and substantially decrease environmental contamination. As the country's energy deficit grows, the federal and state governments are becoming more interested in sustainable and renewable energy sources. One of these is waste-to-energy, which is gaining traction with both the federal and state governments.

Furthermore, as an extension of waste characterization, urban solid waste classification seeks to cogently sort out the material structure in a way that is useful for assessing the viability of future waste processing technologies. This classification focuses on waste-to-energy (WtE) prospects. Combustion, gasification, pyrolysis, and anaerobic digestion are the main waste-to-energy technologies.

All of these include the recovery and conversion of organic carbon from feedstock to a usable energy source. A review of published literature suggests a standard MSW classification system for WtE applications based on an understanding of the processes involved and the working conditions available. There are limited MSW categories for biofuel applications, but all seem to agree on four main classes based on the physicochemical properties of the materials and potential WtE applications for each part, as described in Table 5.5.

Table 5.5 Novel analysis on MSW categorization approaches [11]

Handling methods	Categorization approaches			Example materials
	[7]	[2]	[13]	
Recycling landfill	Inorganic/ non-combustible	Inert fraction	Inert fraction	Metals glass/ ceramics
			Inorganics	Rocks/soil
			Bulky materials	
Composting anaerobic digestion	Organic/ combustible putrescible	Wet putrescible	Compostable organics	Food waste grass clippings
Ethanol fermentation	Cellulosic			
Combustion pyrolysis	Organic/ combustible non-putrescible	Dry combustible	RDF (Woody wastes, paper, plastics, textiles)	Wood waste paper/ cardboard
Gasification	Cellulosic			Natural textiles
Combustion	Organic/ combustible	Plastic		Synthetic textiles
Pyrolysis gasification	Non-putrescible non-cellulosic			Plastics
				Rubber

Since waste-to-energy technologies are still in their infancy, with an emphasis on advanced biofuels, little emphasis has been placed on thermochemical activity classification. It would be useful to develop an adequate category to aid in classifying whether further handling and fractionation of the MSW stream would benefit these applications.

5.2.3 Waste-to-Energy Is a Sustainable Waste Management Option

The waste hierarchy seeks to foster long-term sustainability. In the sense of the waste hierarchy, energy from waste may be classified as either recovery or disposal. To be classified as rehabilitation, facilities must meet the criteria for the process's energy efficiency. For example, the UK government asserts that energy-to-waste must, at the very least, not compete with, and should preferably promote, recycling, reuse, and prevention. Recovering electricity from waste is a realistic way of dealing with it.

Most WtE plants generate electricity. Operators are increasingly looking for ways to use the heat produced, a process known as combined heat and power (CHP). WtE has the potential to play a small but growing role in producing electricity and supplying heat to communities. It is also valuable as a domestic energy source that contributes to energy protection. Consider that expanding the use of residual waste's energy value prior to final disposal will make a more rational and sustainable contribution to our energy policy. With the proper production, refuse-derived fuels could provide stable energy prices for industrial purposes. Waste-to-energy also has the benefit of being non-intermittent, which means it can be used in conjunction with other renewable energy sources such as wind or solar. The environment has a significant impact on the lives of all living beings on this planet. When it comes to waste and its disposal, waste incineration is one of the earliest and most successful methods. Essentially, it is a method in which household and industrial waste materials are burned. The waste materials are converted into ash, flue gas, and heat during this process. Incineration may take place on a small, medium, or large scale, depending on the type of waste materials.

Waste materials or organic compounds, including household, toxic, and medical wastes, are burned in the waste incineration process. Since incineration requires combustion, it is also known as thermal treatment. Nowadays, incinerations aid in the conservation of electricity by preventing it from being lost.

The planning framework should promote the productivity benefits of combined heat and power (CHP). This will necessitate a greater focus on strategic encouragement. Further deliberation is needed in the National Planning Policy Framework and the waste management strategy. Planning policies that provided guidance for how new ventures should use CHP technology at an appropriate scale would provide a major advantage.

While the use of low-carbon and renewable energy is currently promoted in new projects, and many waste-to-energy plants are designed to be “CHP ready,” the reality is that there are so many obstacles to the growth of heat networks without a strategic approach to energy use within our towns and cities. The cost of retrofitting infrastructure to congested utility corridors, as well as the challenge of obtaining reliable offtake of heat at a guaranteed price are among the obstacles that must be overcome for the financial model to function in practice. A clear policy structure in the planning system will help to promote this progress.

As a result, for the sake of humanity’s future, all human processes must be made sustainable. This should include all technical processes as well. One of the most critical technical processes for which technological solutions must be built is energy generation. Except for nuclear and tidal energy, most of the energy generated by humans is derived directly or indirectly from solar radiation (more than 90%). Fossil fuel, which is fossilized solar radiation energy captured by plants, accounts for most of the energy produced today (80%). Due to limited supplies and environmental load from greenhouse gas emissions, mostly CO_2, fossil fuels cannot be considered renewable or sustainable. Furthermore, the reliability of fossil fuel supply is in doubt. Renewable and renewable energy sources, primarily focused on solar radiation (photovoltaic, wind, and so on), are currently receiving a lot of attention. Biomass is one of these outlets. Because of its short carbon cycle, it does not always impact the concentration of CO_2 in the atmosphere. Biomass, if used in a sustainable manner, has the potential to contribute 20–30% of humanity’s energy production.

Currently, biomass accounts for 13% of total energy provision, although this includes almost all conventional cooking and heating in developing countries. For a significant proportion of the human population (more than 40%), biomass is the sole source of energy. It is estimated that a significant portion of agricultural and forestry waste (equivalent to 50% of global crude oil production) can be converted into energy while avoiding undesirable food and feed/energy competition. Longer-term, the production of high-efficiency energy crops can be considered. To some degree, biomass can be (co)fired in modern equipment alongside fossil fuels without much pretreatment, as in the production of electricity in coal-fired power plants (green electricity). However, much of the current R&D effort is dedicated to transforming biomass into improved energy carriers that are equal to, or better than, the current fossil-based fuels.

Energy from waste has the potential to substitute a portion of conventional fossil fuels with biodegradable waste, thus reducing greenhouse gas emissions associated with electricity generation. In terms of carbon footprint, energy from waste is usually a more environmentally friendly method of waste disposal than landfilling residual waste. This, however, is based on the plant's productivity as well as the amount and type of biogenic material present in the waste (high biogenic content makes energy from waste inherently better and landfill inherently worse). The debate continues about whether biomass combustion emissions (biogenic or short-cycle fuel) should be considered carbon neutral.

5.2.4 International Characterization Process of Energy-to-Waste Technologies

Tolerance for zero waste means empowering people to produce without or as minimal waste as possible. It means that nonrenewable resources must be conserved in the manufacture and distribution of goods and services, and waste and emissions must be avoided or held to a minimum. Waste management encourages sustainability in practices such as resource recovery, recycling/reuse, and composting by reducing raw material demand during processing as well as disposable waste, thus conserving nonrenewable resources. Individuals who care about the environment are more likely to employ pro-environmental behaviors such as recycling, composting, and source reduction. According to research, the public's environmental attitudes in developed countries have been growing and widening to include a wide range of demographic groups other than urban, well-educated, and wealthy groups [14]. Recycling schemes, for example, have increased in the United Kingdom, Canada, and Great Britain, making recycling more accessible to more people and, as a result, lessening the impact of environmental issues.

Although little effort has been made in other countries to identify MSW, other attempts to describe waste have been made. This is because a greater emphasis is being placed on waste management protocols that address landfill alternatives as land space becomes scarce and in areas with a significantly higher population density. For completing urban solid waste composition studies, the ASTM International standards organization has established a methodology. Many jurisdictions use it to some degree because it allows for the customization of sample size and sorting categories to meet the needs of the study community [12].

A material flow approach is used in many state-wide studies in the United States to measure waste composition. This is finalized by comparing the total quantity of material waste in the waste stream with output data for the products that join the waste stream [11]. Many studies are also concerned about the impact of seasonality on waste streams and how this can influence the composition of the MSW. Greater humidity content due to higher organic matter during the roomier season can lessen conversion efficiency. The amount of waste does not seem to be affected by the season.

Around the world, most methodologies to characterization studies depend on demographic relationships to collect and compare fractions of the urban waste source. This outlook is useful for waste management approaches, but it is not useful for characterization for waste-to-energy applications. Although not all methods necessitate additional waste stream sorting, the proficiency of the practice can be enhanced if this is achieved. Magnets and sieves may be used to separate inert materials from the waste stream, such as metals, glass, and soils. In thermochemical conversion technologies such as gasification, inert materials cannot contribute to the energy potential and instead reduce the sample's total energy density. The sorted MSW is often shredded to provide a more consistent feedstock called waste-derived fuel (RDF-3). This RDF is the material sent to energy-efficient waste plants [11].

A solitary ASTM International standard detailing the terms of the RDF classified them according to the process stage that was performed before it was used as a final feedstock (Table 5.6); due to restricted use by industrial applications, the standard was withdrawn; an equivalent standard exists for coal. These classifications may help to compare the processing levels needed for various WtE systems.

Table 5.6 RDF categorization [11]

Category	Explanation
RDF-1	Wastes used in discarded form.
RDF-2	Wastes processed to coarse particle size with or without ferrous metal separation.
RDF-3	Processed to remove metal, glass, and other inorganic materials. Particle size such that 95 weight % passes through a 2-in. square mesh screen.
RDF-4	Combustible waste processed into powder form, 95 weight % passing 10-mesh screening.
RDF-5	Combustible waste densified (compressed) into the form of pellets, slugs, cubettes, or briquettes.
RDF-6	Combustible waste processed into liquid fuels.
RDF-7	Combustible waste processed into gaseous fuel.

5.2.5 *Waste-to-Energy Projects*

Waste production continues to grow, and landfills consume a significant amount of land, leaving cities surrounded by garbage and solid waste. In recent years, MSW incineration has increased steadily. Incineration methods can minimize the volume and mass of MSW by up to 90% and 80%, respectively, and incineration with energy recovery is one of the waste-to-energy (WtE) technologies [15].

According to Adapa et al. [16] the rising of energy demand has caused a stalemate among established energy sources, regardless of whether they are thermal, nuclear, hydro, or solar. It stresses the need for an alternative, highly feasible, and long-term energy source. According to the paper, municipal solid waste (MSW) has long been a safe and effective choice for waste-to-energy conversion. The paper also discusses the various conversion processes, such as incineration, pyrolysis, gasification, and biodegradation. The above technologies are compared using various physical and chemical parameters, with the aim of ensuring the environmental sustainability of waste-to-energy (WtE) systems. Their research concludes, based on assessment results, that biological approaches are best adapted for waste-to-energy conversion with the least environmental impact.

Methods such as pyrolysis, incineration, and gasification are quite efficient and productive but are also very dangerous because they emit dangerous gaseous emissions, which, without a doubt, contribute to global warming and the greenhouse effect. Fruergaard and Astrup [17] presented a study on the most efficient waste-to-energy conversion in life cycle assessments (LCA). The article states that two forms of urban solid waste can be used to produce electricity. Mixed high-calorific waste, one type of municipal solid waste, is better for the production of solid retrieved fuels, abbreviated as SRF, whereas organic waste is separated by the other. It is explained that co-combustion is equivalent to mass-burn incineration for solid recovered fuels. In their study, incineration was modelled for the case of mass-burn incineration. Both scenarios with and without energy recovery were included in the model. The biogas generated by anaerobic digestion can be used for a diversity of targets, involving transportation fuel, heat generation, and power generation, according to the report. There are various related findings for resource and energy use in life cycle assessments, such as emissions to air, soil, and water, downstream processes, upstream processes, and so on.

There are two distinct energy systems that must be considered when making energy substitutions. One is the current Danish scheme, which is based on fossil fuels. The other energy system is the possible failure system, which is entirely reliant on renewable energy. The article demonstrates that mass-burn incineration of solid recycled fuels combined with energy recovery save money in a variety of ways. Co-combustion, on the other hand, is much superior to global warming. If we use all of the heat from the incineration, there are two solid recovered fuel alternatives that are tested and compared to each other. In certain types of impacts, incineration with energy recovery is safer and superior to anaerobic digestion for organic waste.

The study by Peterson et al. [18] looks at the Baltimore Clean Air Act and suggests that the city needs a new waste management system. The passage of the Baltimore Clean Air Act, as well as the impending closure of the Wheelbarrow garbage incineration facility, indicate that current waste management programs in Baltimore must be plowed, according to the report. The paper discusses three key policy concepts that are inspired by other cities' "Zero Waste" policies. Policies can promote residential and business waste management, as well as investment in an improved waste disposal system and waste incineration subsidy schemes.

The Wheelabrator Baltimore plant, as a green waste disposal alternative, provides a modest energy return at the same level as traditional waste disposal while emitting greenhouse gases and harmful pollutants. Closing the incinerators creates a slew of new problems, and the only way to deal with the inevitable increase in waste capacity is to take proactive measures. To make this possible, waste management policy choices and plans have been proposed. The first piece of advice is to use financial incentives to encourage businesses and residents to minimize waste. Most of the waste usually ends up in landfills, which can be eliminated by reducing waste sent to garbage incineration. In the short term, the priority should be on industries that generate the most waste, while in the long run, the emphasis should be on built-up recycling and zero waste initiatives. The second suggestion is to concentrate on recycling and composting, as well as to extend existing waste sorting facilities by constructing new compost facilities. The third proposal is to exclude biomass and waste incineration from the Tier 1 renewables band, as well as the tax incentives that go along with it [18]. According to the article, the method has both advantages and disadvantages. Although quick-response services are necessary when there are large amounts of waste in a landfill, focusing on residents would generate more awareness and investment. Additionally, outreach services can be extended.

However, when the first guideline is introduced, community and company engagement should also be present, and the one who participates will be given the Green Business designation. The benefit of the second approach, which is to move toward biogas plants, is that it would help to eliminate harmful elements in the environment while still producing compost. Many people will lose their jobs because of the closure of WtE facilities, further investments will be required, and the pace at which an existing landfill reaches capacity will increase. According to them, removing waste and biomass incineration from the third strategy will improve people's health chances because it emits more carbon dioxide than coal. But, without them, it will be difficult to meet renewable requirements, which may lead to an upsurge in the price of energy.

A study by Bruner and Rechberger [19] has emphasized the value of incineration from the perspective of urban metabolism, demonstrates that incineration is critical for long-term waste management, and provides a technical overview of municipal solid waste incineration over time. It has been shown that human actions often result in waste. Without question, as waste management becomes more complicated and material turnover increases, achieving the objectives of "defense of men and climate" and "resource conservation" becomes more difficult. Waste incineration, which was first implemented for volume reduction and sanitary reasons, has undergone extensive growth. Waste to energy plants, when combined with waste reduction and recycling measures, play a major role in achieving waste management targets. Environmentally friendly emissions are ensured by sophisticated Air Pollution Control (APC) systems. Finally, it was discovered that incinerates are both essential and special for the complete destruction of hazardous organic materials.

Anwar et al. [20] discuss how greenhouse gases can be converted into fuels and useful goods. Global warming and climate change are mostly caused by carbon dioxide emissions. Global warming and climate change are posing a significant threat to the environment, human life, and ecosystem. Carbon dioxide emissions have reached dangerous levels, resulting in disasters such as droughts, tornadoes, hurricanes, flooding, and wildfires all over the world. Both tragic incidents have resulted in thousands of deaths and have had a negative impact on the economic growth of many countries. The use of fossil fuels also increases local air pollution, such as winter smog. Water shortage problems are becoming more prevalent as the world's population grows. Carbon dioxide levels must be reduced to avoid any of these catastrophic events. All these issues can be addressed by extracting CO_2, storing it, and using it to make biofuel and other useful chemical products. This can be used as a substitute for traditional fuels. As a result, the economic and environmental conditions will be improved, and many jobs will be created. Additionally, this can be used to desalinate seawater to provide clean water.

The reduction of fossil fuel consumption and the conservation of resources have become gradually more crucial in current years. Greater recycling rates for usable materials (e.g., materials) and recovery of energy from waste streams could therefore be a key role in replacing virgin material production and preserving fossil reserves. This is particularly important in the case of residual waste, which is normally incinerated in the United States. Several energy consumption scenarios for two outputs were evaluated. The use of liquid fraction for biogas production and co-combustion in existing power plants were found to be the most environmentally friendly (especially in terms of global warming) and energy-efficient option. The waste refinery's energy and environmental efficiency is primarily influenced by opportunities to reduce energy and enzyme consumption.

The amount of waste generated is directly proportional to the rise in gross domestic product, the rate of population growth, and lifestyle changes. Solid waste can be used to generate and utilize energy, particularly in megacities. The produced waste, which has the capacity to generate electricity, is scattered across the ecosystem due to a lack of management. It can be used to recover energy in the form of biogas, electricity, and fertilizers, among other things. These beneficial components are currently released into the environment because of open burning and dumping or into groundwater because of bad landfill conditions. Most of the budget of most cities is set aside for solid waste programs. However, only about half of the solid waste produced is collected, with the remainder being improperly disposed of at landfills, along roadsides, or burned openly without regard for air and water pollution control.

The exploration of various types of waste management technologies is hampered by a lack of knowledge, financial and institutional capacities, and in this regard, only a small number of treatment plants, i.e., composting plants, are operational in Pakistan. Consequently, it is important to analyze the socioeconomic and environmental implications of various types of waste-to-energy technologies that are currently in use around the world and to identify the adequate treatment facility suitably based on the criteria listed.

5.2.6 Waste-to-Energy Scenario

The world's energy supply is currently dominated by fossil fuels. However, since fossil fuel reserves are small, generating energy from them is not a viable choice. Furthermore, as they burn to generate electricity, they emit greenhouse gases (GHG). Even with best practices, coal-fired thermal power plants emit 532 g of CO_2 per unit of electricity generated [21]. Global warming is a serious consequence of these emissions. However, over the last 10 years, global primary energy consumption has increased by nearly 2%/year. Figure 5.3 depicts the global share of various sources of primary energy consumption [22].

Oil is thought to be the forerunner, preceded by gas. However, these resources' reserves are finite, and their combustion emits significant GHG. These two factors have compelled scientists and policymakers to look for alternative energy sources. At various summits, world leaders introduced various strategies to reduce GHG emissions and protect the atmosphere. Table 5.7 depicts some of the most significant summits. These gatherings serve as a catalyst for the advancement of energy harvesting technologies from renewable energy sources. The key goal of summits was to reduce carbon emissions. Each nation was given a goal of limiting carbon emissions to a certain amount to minimize environmental pollution effects such as global warming.

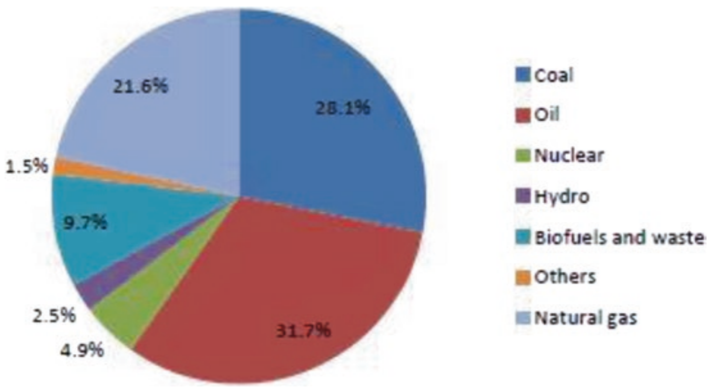


Fig. 5.3 Stake of various energy resources in core energy expenditure in the world [22]

Table 5.7 Various protocols for limiting carbon emission targets [4]

Serial No	Milestones	Venue	Year	Key element
1	Kyoto Protocol	Kyoto, Japan	1997	The participating countries were given emission targets.
2	Cancun Agreements	Mexico	2010	It was agreed that developed countries would contribute $100 billion USD to a climate security fund for developing countries.
3	Durban Platform for Enhanced Action	South Africa	2011	The thoughts of all United Nations representatives on the formulation of a legal system were considered.
4	Paris Agreement	Paris, France	2016	Global warming is regarded as a serious hazard. The developing countries' unique areas of fund and technology transfer are established.

5.2.7 Advantages and Disadvantages of Renewable Energy

Renewable energy has the following advantages [4]:

1. It is generally clean energy.
2. The operation and the maintenance cost are low.
3. It increases regional/national energy independence as, unlike fossil fuel, these reserves are not confined within a particular boundary.
4. Accelerates rural electrification in the developing countries.

Despite all these advantages, renewable energy has the following disadvantages:

1. It is intermittent in nature, i.e., the electricity can be generated when the resource is available but not when it is actually required.
2. This gives rise to the necessity of suitable energy storage systems. The conventional practice is to store electricity in a battery. These batteries affect the environment and economy. There are also capacity limitations.
3. The initial capital investment is high.

It should be remembered that renewable energy has many benefits as well as drawbacks. Renewable energy has several drawbacks that are not only technological but also socioeconomic. As a result, appropriate need-based conversion technologies must be developed for the improvement of renewable energy systems. Renewable energy technology has not yet evolved to the point that it can be used to construct large-scale power plants. Furthermore, storage is a significant problem due to sporadic availability. The most convenient method of electricity storage now is electrochemical storage, which involves storing electricity in a battery and then releasing it when required. However, there are power, environmental, and economic constraints to electrochemical storage. The system's cost is high due to the high cost of batteries. Batteries typically need to be replaced every 5 years, while most renewable energy systems last for 20 years or longer. Furthermore, the batteries' disposal is not environmentally friendly. As a result, hybridization of various renewable energy systems is needed, which entails combining various renewable energy systems such as solar, biomass, wind, and others into a single system. As a result, distributed generation based on local resources may be a viable choice for energy systems. These systems are created to meet a variety of local utility demands while considering technical, socioeconomic, and environmental constraints.

5.2.8 The Nature of the Waste Considered for Renewable Energy

Waste management firms are experiencing a period of uncertainty because of the push to reduce landfill and dumpsite waste. When governments and businesses seek to extract value from waste, they must implement more sustainable strategies. Recycling and reuse will become more essential because of this. Strategies for waste-to-energy conversion are being built, and projects are being planned. Waste-to-energy converts solid waste that would otherwise be disposed of in landfills into energy by burning it and leaving a small amount of ash that can be reused as road or building aggregate, with the remainder (such as hazardous waste) being disposed of in a landfill.

The material produced by individual households and some small businesses is known as municipal solid waste (MSW). It reflects the historically discarded and disposed of post-consumer spent and surplus products. In the meantime, commercial and industrial waste (C&I), consisting of spent, unused, or unwanted materials occurring during the primary manufacturing, can be considered for use in WtE. As it is presumed that these will be channelled to some better treatment before being introduced as a prospective fuel, they will be used as process inputs into another operation. Biomass is an example of waste from industries that are abundant in Malaysia. Furthermore, construction and demolition (C&D) waste can be used as a waste resource in WtE. Building demolition or alterations, as well as spent or surplus materials provided by construction and engineering activities, are examples of this form of activity.

The products from these three waste streams are by their very nature combined or dissimilar. This is a direct result of the conditions surrounding their disposal, and it will have a significant impact on how the products are used in the future if they are not naturally discarded for landfill disposal. The ability to reuse or recycle materials is greatly improved when they can be presented in specified or homogeneous streams, as is the case with recycling of domestic cans and paper, source-separated garden waste, or source-separated wood, metals, glass, and plastics from C&I or C&D waste.

Even if the products in urban waste are uncertain, they all have certain wide-ranging characteristics. These wastes would generally contain:

1. Hydro organic element
2. : This material is derived from food waste, soiled paper, and organic garden products and originates mainly from lignocellulose biomass.
3. A biologically inactive or slow-burning high-calorific element: This substance includes plastics, textiles, footwear, and a small amount of wood, cardboard, and paper. It is primarily composed of hydrocarbons derived from crude oil, with some lignocellulosic material carried over.
4. Metals: This category of materials includes ferrous (iron and steel) and nonferrous (aluminum, copper, and lead). Metals may be extracted from the waste material in its original state.
5. A non-reactive element: This category contains ceramics, soil, grit, broken glass, and debris. These materials can be easily removed from the waste material that originally produced them.

As a result, the location or geography of a possible source of urban waste is a critical factor to consider when determining the feasibility of a suitable energy recovery route. Transportation issues associated with aggregation to create viable amounts, as well as the transmission of any generated electricity, are both characteristics that must be considered when verifying the definitive feasibility and sustainability of the WtE project. The following subtopics emphasize biomass and urban solid waste as potential energy resources.

5.2.8.1 Biomass Energy

Strong carbonaceous content extracted from plants and animals is referred to as biomass. These include crop and forestry residues, animal waste, and food plant waste. Biomass is organic matter extracted from terrestrial and marine plants and natural renewable energy sources over a limited period. It is a solar energy derivative because plants develop CO_2 from the atmosphere and transform it into hexose represented by the reaction:

$$6CO_2 + H_2O \xrightarrow[\text{photosynthesis}]{\text{sunlight}} C_6H_{12}O_2 + 6O_2$$

Biomass does not contribute to CO_2 emissions into the atmosphere because it absorbs the same amount of carbon that it releases when used as fuel. It is a superior fuel since biomass energy is carbon neutral. About 90% of rural households and nearly 15% of urban households use biomass fuel. Wheat, maize, and sugarcane are examples of agricultural products rich in starch and sugar that can be fermented to generate ethanol (C_2H_5OH). Ethanol (C_2H_5OH) can also be generated by distilling biomass containing cellulose, such as wood and bagasse. Both alcohols are suitable for vehicle fuel and can be combined with ethanol to produce biodiesel. The example of biomass energy from agriculture is shown in Fig. 5.4. The description of biomass energy resources is shown in Fig. 5.5.

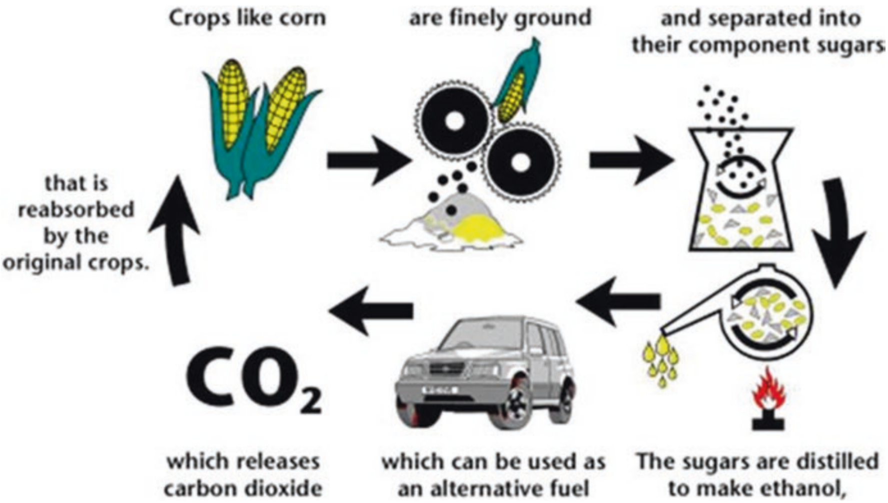


Fig. 5.4 Potential renewable energy from agriculture biomass waste

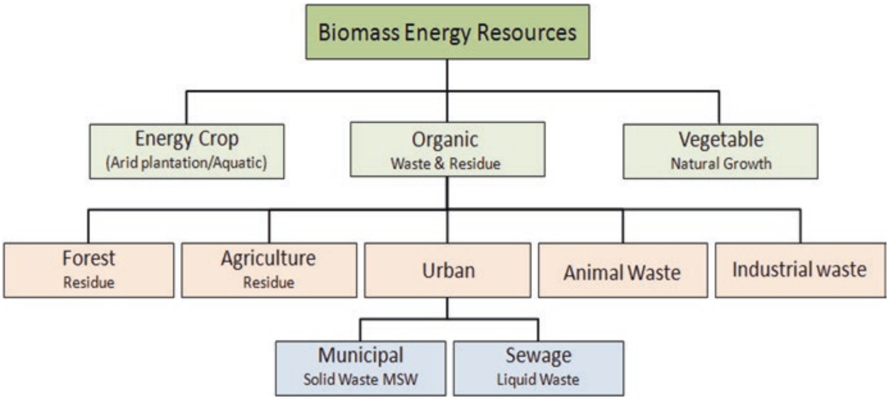


Fig. 5.5 Potential biomass energy resources

Energy initiatives that use agricultural biomass to aid individuals or specific investor groups at the expense of others and the entire community face resistance. Policymakers, on the other hand, often neglect the social, economic, environmental, and spatial conflicts associated with agricultural biomass-derived energy. According to Geels et al. [23], multi-level renewable energy research is required, including considerations of different concerns, values, skills, and resources among citizens, growers, local and regional governments, and national governments, whose strategies should be explored.

Crop residues are a plentiful natural resource that is simple to obtain and store. Rice husk, wheat straw, corn cobs, cotton stick, sugarcane bagasse, groundnut, and coconut shells are examples of these materials. For use as a clean fuel, these are turned into briquettes or pallets. There are high-efficiency solid fuels known as "biofuels." Sugar and rice, the world's two main tropical food crops, are estimated to have a combined energy content of about 18 EJ, which is equal to the combined energy content of temperate crops. Fuels are now being used in large quantities:

1. Bagasse, the fibrous residue of sugar cane, is used as a fuel in sugar factories to generate steam and electricity for the factory. Facts: (a) Transporting bagasse might not be cost-effective; (b) Expanded waste recovery, combined with improved conversion performance, could result in up to 50 GW of generating power from sugar manufacturing around the world; (c) Another idea is to make ethanol out of bagasse.
2. Rice husks are the most ordinary agricultural residues in the world, accounting for one-fifth of the dry weight of un-milled rice. While having a high silica and ash content as compared to other biomass fuels, their consistent texture makes them ideal for gasification technologies. Several countries, like Indonesia, China, and Mali, have successfully operated rice husk gasifiers.

Forests, whether natural or planted, provide a plentiful supply of timber, fuelwood, charcoal, and raw materials for paper mills and other industries. Eucalyptus, Neem, Kikar, and Gulmohar are fast-growing trees that are cultivated along canals, railways, and on low-quality ground. In sawmills, wood, sawdust, and bark residue are produced. The forest also has a lot of foliage and logging debris. A significant characteristic of forest residue is its calorific value, which ranges from 4399 to 4977 kcal/kg for softwood foliage and 3888–5219 kcal/kg for hardwood plants. Here are a few things about forest biomass residue that you should know.:

1. Switchgrass, which can be found in prairies remnants, along roadsides, pastures and as wind breakers around farms.
2. Hardy, perennial grass can grow up to 1.8–2.2 m.
3. As a source of forage for animals, in wildlife habitats, or as a ground cover to prevent erosion.
4. Can generate up to 1000-gallon ethanol/acre.
5. An alternative that is currently not feasible needs 45% more fossil energy than the fuel generated.
6. More research is needed to improve the efficiency of the conversion process.

De Wit and Hoppe [24] report that agricultural policy and technological progress are key factors in exploiting the capacity of agricultural lands completely to generate energy crops. However, the absorption of energy crops and renewable energy derived from agricultural biomass is determined by a complex web of interconnected, multidimensional political, governmental, cultural, and economic processes, not only technological ones [25]. According to De Silva and Horlings [25], there is no systematic diagnosis and no holistic approach to resolving how and why low-carbon energy is not being used in rural areas.

The rapid growth of the population is increasing the market for energy and new technologies. Oil, natural gas, coal, and other fossil fuels are used in several science and technology applications, but the main drawback about these conventional fuels is that they are nonrenewable sources, implying that they cannot be used again after one use. As a result, renewable energy sources must be used in science and technology [26]. Bioethanol is one of the most useful energy sources that can be replenished by using crop residue. The aim of using biofuel is to substitute fossil fuels, which lead to emissions and the greenhouse effect. By processing sugar and ethanol for the markets, the production of ethanol from sugarcane benefits not only the climate but also the rural economy, which is Brazil's main source of income. In addition, a byproduct of the ethanol process, bagasse, can be used to generate thermal and electrical energies. As large amounts of bioethanol are generated from sugarcane through fermentation, the residual product known as bagasse should be stored and utilized because it is extremely valuable in the production of thermal and electric energy [27].

Ethanol is the chemical compound ethyl alcohol which is a colorless flammable liquid. It is a renewable source of energy that can be used in place of petroleum products. Ethanol can be manufactured using an assortment of biomass materials that include sugar, starch, and cellulose. Three of the most well-known feedstocks are sugarcane (sugars), paddy rice (starchers), and grasses (cellulose).

Figure 5.6 shows the processes of bioethanol production from different resources. Notably, molasses is a byproduct of the sugar factory from which the remaining 40–47% sugar is unable to be processed conventionally. However, it can be fermented to produce alcohol using yeast (*saccharomyces cerevisiae*). Meanwhile, Fig. 5.7 depicts the global energy expectation statistic up to 2013.

Grains high in carbohydrates are made up of starch crops. The structure of starch $(C_6H_{10}O_5)n$ is complex, with several glucose molecules connected together in a long chain called disaccharide sugars. Prior to fermentation, the starch chain must be converted to sugar. Starch cannot be converted into fermentable sugars by yeast culture. Hydrolysis of starch with dilute H_2SO_4 or an enzymatic process may be used to convert it. Prior to starting ethanol processing, starch is converted into maltose and glucose. Meanwhile, cellulose found in wood, grasses, and crop residue contains a long chain of sugars, as well as lignin, which prevents sugar hydrolysis

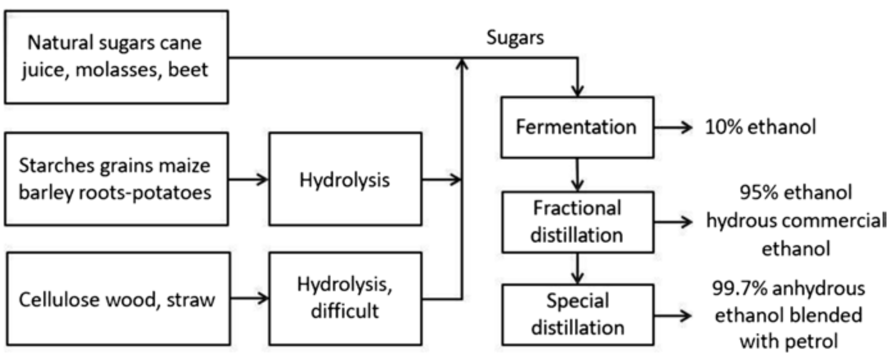


Fig. 5.6 Bioethanol production

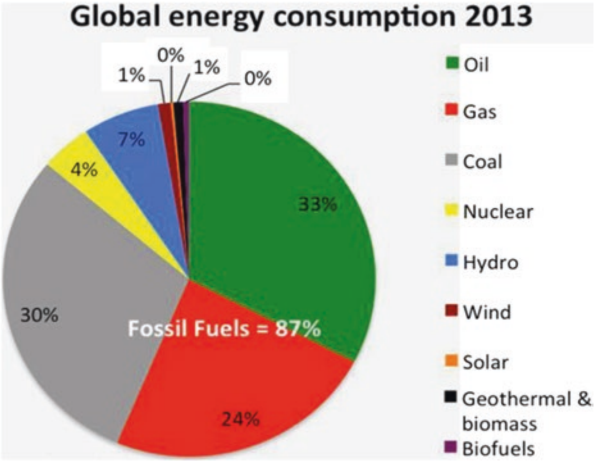


Fig. 5.7 Global energy consumption [28]

in plants. Polysaccharides are a complex substance that is more difficult to convert to simple sugars than starch. Cellulosic content is transformed by varying the acid concentration, operating temperature, and reaction time during special hydrolysis with dilute H_2SO_4 at elevated temperatures of 180–200 °C, which enables the product sugar to decompose into glucose and finally ethanol.

Brazil is the country that widely used ethanol derived from biomass in its Pro Alcohol program. Some facts related to the Pro Alcohol program in Brazil can be summarized as follows:

1. Over 90% of new automobiles run on ethanol derived from sugar residues.
2. The leading profitable biomass system in the world.
3. Founded in 1975, during a period of high oil prices and low sugar prices.
4. Stop fossil fuel imports for the first 25 years, saving $40 billion in direct interest savings on international debt.
5. At times, production approached 15 billion L/year.
6. Currently, most vehicles operate on gasoline with a 26% ethanol content.
7. According to 1999 estimates, the policy was reducing annual greenhouse gas emissions.
8. A reduction of nearly 13 tons of carbon dioxide emissions.
9. The economics of ethanol production are highly speculative.
10. Sustainability is critically dependent on global sugar and crude oil prices, which have fluctuated widely and often rapidly over the last 30 years.

5.2.8.2 Municipal Solid Waste (MSW)

There were no sanitary control schemes in place prior to 1800. Garbage was burned or dumped in alleys, streets, and rivers [5]. As the 1800s approached, several families dug disposal pits as a substitute. Both wild and domestic animals were used to dispose of waste in the 1800s. Cholera and yellow fever epidemics prompted local governments to improve sewage treatment and water sources by the end of the 1800s. Instead of developing an integrated waste management system after World War I (WWI), contractors for waste management were outsourced. Multiple transfer stations were built to serve small household units after a common disposal site was found. During the 1930s and 1940s, the federal government imposed location limits, preferring dumpsites to be built away from waterways. The first sanitary landfill in the United States was built in California, USA, in 1934, and the practice grew in popularity.

According to the United Nations Environmental Program in 2012, there is a huge possibility for energy recovery from solid waste based on continuously developing urban waste management systems and a rise in waste-to-energy investors to the tune of $1 billion USD [6]. Furthermore, compared to other sources of energy, waste-derived energy is simple to generate an inexpensive and would be a welcome alternative during these difficult economic times.

The development of municipal solid waste (MSW) as a thermochemical conversion feedstock for advanced biofuels is underway. Edmonton formed the first waste-to-biofuels partnership with Enerkem Alberta Biofuels; however, Canada has only recently begun to consider increasing landfill diversion rates through the incorporation of new technologies and programs, owing to a glut of available land and a lack of inducements to support make these new technologies as cost-efficient as landfill. A robust categorization system is needed to realistically discover the prospects for energy recovery from MSW.

Most developed countries, including the United States, Europe, China, Singapore, and Japan, produce energy from solid waste. Municipal solid waste (MSW) has been broadly used in recent years to create waste-to-energy (WtE) through conventional technologies such as direct combustion (e.g., incineration/combustion, pyrolysis, and gasification) or the processing of flammable gases such as methane, hydrogen, and other synthetic fuels (e.g., anaerobic digestion and refuse-derived fuel). Combined heat and electricity is the preferred option to increase energy productivity by using MSW. MSW that has been discarded can be used to generate electricity and reduce greenhouse gas emissions. Advanced MSW management technology with the added benefit of energy extraction from solid waste represents an encouraging choice for solving the country's waste discarding problems [29].

MSW refers to combustible and non-combustible household, commercial, and industrial wastes that are typically disposed of in urban landfills. Because up to 80% of the carbon content of combustible MSW is extracted from biomass, it is widely referred to as a renewable fuel. MSW's primary environmental concerns center on the potential negative impact of inefficient waste management practices on human health and the climate, including soil and water contamination, air quality, land use, and landscape. Current findings reveal that the new MSW disposal systems of landfilling and incineration (mass burn or combustion) are unsustainable due to their high greenhouse gas emissions [30].

MSW is currently disposed of in sanitary landfills, where it produces fuel gas, a valuable green energy source. Biogas is made from sewage that has been properly treated. Sewage is a liquid waste that is transported by water and is meant to be extracted from a community. It is more than 99% water and is exemplified by quantity or flow rate, physical condition, chemical and toxic components, and bacteriological condition. It is also known as domestic or municipal wastewater. Greywater (from drains, tubs, showers, dishwashers, and clothes washers), blackwater (the water used to flush toilets, along with the human waste it flushes away), soaps and detergents, and toilet paper make up most of the waste (less so in regions where bidets are widely used instead of paper). Surface runoff can be contained depending on the path it takes back to the ecosystem.

In several cities throughout North America, landfilling is still the primary method of disposing of MSW. While some cities are building sanitary or modified landfills to reduce leachate pollution, the issue of greenhouse gas emissions from landfills such as methane (CH_4) and hydrogen sulfide (H_2S) remains unsolved. Methane has a greenhouse gas impact that is 20 times greater than carbon dioxide [31]. Composting, anaerobic digestion, and ethanol fermentation are examples of biological process-based technologies with low reaction rates. The organic components of MSW are commonly used as compost or fuel for biological processes that produce a marketable product [32].

MSW is made up of discarded paper, plastic, food scraps, textiles, glass, metals, and other materials. Plastics, paper, lignocellulosic materials (wood, leaves, food scraps), textiles, and rubber are among the organic (carbon-based) waste stream components that can be converted into energy. Although not all technologies necessitate additional waste stream sorting, doing so will improve the efficiency of the process. Magnets and sieves may be used to separate inert materials from the waste stream, such as metals, glass, and soils. In thermochemical conversion technologies, including gasification, inert materials cannot add to the energy potential and just lower the sample's total energy density. After being processed, MSW is often shredded to produce a more standardized feedstock known as refuse-derived fuel (RDF-3). This RDF is the raw material that is dispatched to waste-to-energy plants.

MSW is made up of both organic and inorganic fractions that come from various sources within a municipality [33]. Construction and demolition (C&D) waste and wastewater treatment sludge are usually excluded [7]. Most MSW streams are currently collected by municipalities and disposed of in sanitary landfills. Waste recovery plants are used in some areas to extract recyclable or compostable items from the waste stream. Other municipalities have turned to incineration facilities to minimize the amount of waste sent to landfills. As the land-dwelling zone available for landfilling has shrunk and environmental concerns have grown, there has been an increasing need to find alternative waste management solutions around the world. Due to limited spaces, these techniques have been established in leading European countries and other highly populated regions around the world.

Table 5.8 Current procedures for classifying urban solid waste [11]

Basis for segregation	Considerations used for segregation
Waste type	Density, shear parameters, liquid/plastic limit, permeability
Material groups	Part of composition
Organic, organic materials	Degradability (easily, slowly, non) Shape (hollow, platy, elongated, bulky)
Degradable, inert, deformable materials	Strength, deformability, degradability
Material groups	Size, dimension
Soil-like (3-D structure), other	Index properties
Soil-like (3-D structure), non-soil-like (2-D structure)	Material groups
Mechanical properties	Material properties, weight, size, shape, organic, inorganic, soil-like, non-soil-like
Material type, product type	Part of MSW composition
Thermochemical characteristics	Proximate and ultimate analysis

To test thermochemical waste disposal technologies, jurisdictions must first analyze how they presently organize their waste streams to decide which technologies will be appropriate in the future. A framework for assessing a city's energy potential from waste sources would be an invaluable tool for directing the transformation of Canada's waste management platforms. The majority of current MSW classification schemes (Table 5.8) are focused on the material form or physical properties, according to Charley [11].

The most used classification scheme is based on material characterization, which is standardized by the US Environmental Protection Agency (USEPA). This method formulates the qualified elements of each material present in an MSW sample, which can be inferred to whole inhabitants. The list of materials may be adapted to satisfy the requirements of the prerogative that accomplishes the characterization. The findings of a characterization study can be used to assess the potential for physical, biological, and chemical production, as well as energy recovery and landfilling.

The organic, putrescible, or cellulosic properties of a material can help determine its composition in an MSW stream; these physicochemical properties imply whether energy can be extracted from a material, and if so, how much energy can be extracted. American Society of the International Association for Testing and Materials Standards [12] used this information to create a classification structure for energy recovery from MSW (Fig. 5.8), which incorporates various categorization methodologies to include a system for identifying appropriate energy-generating methods founded on the waste's material structure. This outline can then be applied to the findings of a characterization analysis to verify the best energy recovery approach for a given jurisdiction. MSW is increasingly being investigated as a potential feedstock for biofuels applications globally, enabling the creation of more environmentally friendly energy solutions as well as a more efficient method of disposing of waste that was historically disposed of in landfills.

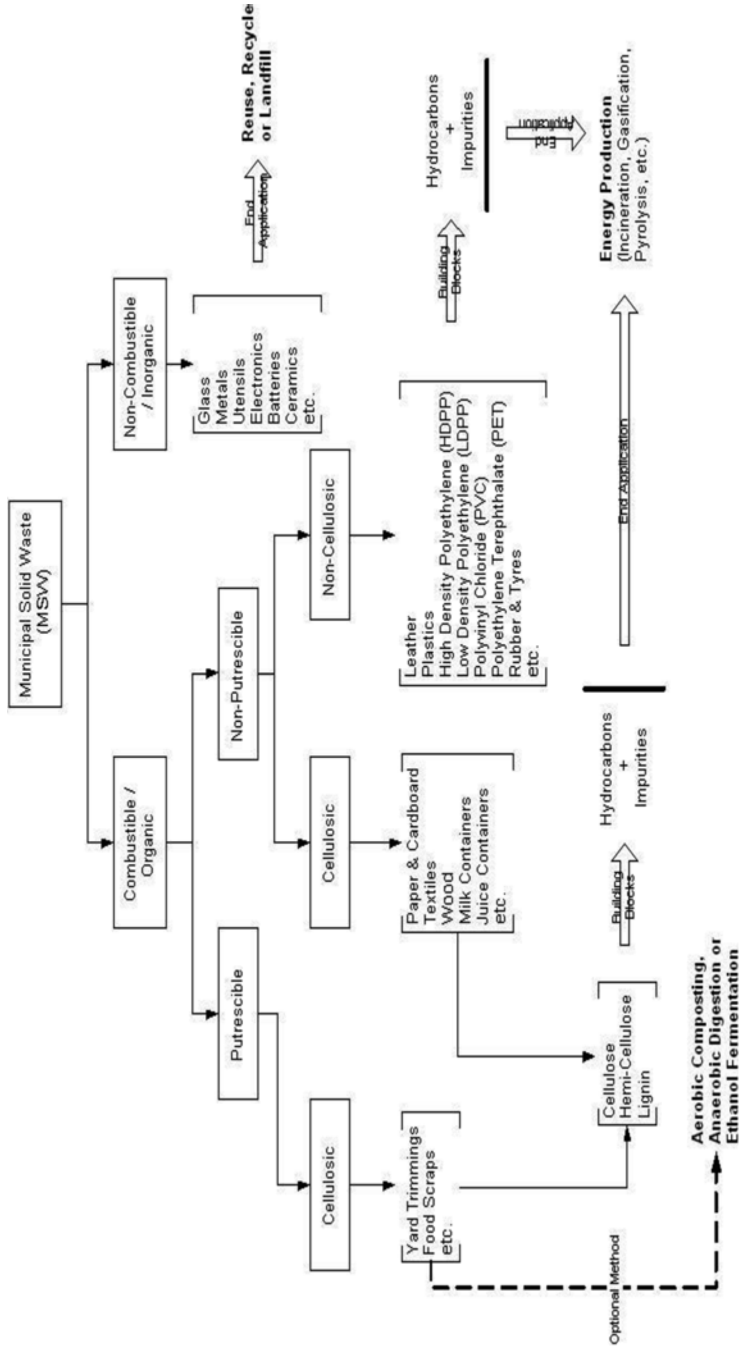


Fig. 5.8 MSW categorization scheme for energy recovery [7]

5.3 Energy from Waste Infrastructure

The rule of thumb of waste management is by following Lansink's stepladder—setting the following priority for waste management: prevention > recycling > incineration with energy recovery > incineration > landfilling. Currently, waste management has strictly highlighted recycling and reinvigorating the waste and, if possible, waste prevention; zero waste. Annually human population keep increases thus, it proportionally reflects the accumulation of solid waste as clearly for the example, the total municipal solid waste (MSW) generation in the EU25 has increased from about 150 million tons in 1980 to more than 250 million tons in 2005 and is forecasted to reach 300 million tons by 2015 [34]. The big issue rise is where all these huge wastes need to be dumped? All the landfills are right now having a limited space; thus, serious concern needs to be highlighted here. Proper methods to deal with the entire categories of wastes are needed because without many people realize all these wastes can be converted into a value-added subject, energy. Thus, it will lead to a sustainable environment and achieve the united nation (UN) aims at 17 Sustainable Development Goals (SDGs).

5.3.1 Energy Recovery Concepts

Uncontrolled municipal solid waste (MSW) and waste disposal issues have raised awareness of sustainable waste management. Worldwide, waste-to-energy (WtE) systems are being developed to recover energy from garbage. Material recovery and recycling have become more important in MSW management. While there is a high level of awareness and concern for waste prevention and sustainability, the overall amount of MSW generated is expected to continue to grow over the next decade [34]. In developing a more sustainable waste management approach, WTE technologies are vital. This subchapter discusses waste conversion technology for the energy recovery. While certain WtE processes allow raw (i.e., as received) MSW as feed, the bulk of WtE practices preprocessed MSW to minimize changeable and/or inconsistent operational conditions, and also unpredictable product quality.

5.3.2 Waste-to-Bioproducts (WtB) and Waste-to-Energy (WtE)

The waste-to-bioproduct (WtB) commonly focuses on the recovery of the unseen potential energy in the municipal solid waste (MSW); thus, the typical term that is frequently highlighted is waste-to-energy (WtE) which is a recent concept waste management strategy. The primary goal is to dispose of garbage and transform it into resources that may be used to make a variety of products that will help to reduce greenhouse gas (GHG) emissions. Solid waste (SW) is a carbonaceous and nutrient-rich biomass that is frequently underappreciated in society.

Talking about energy, the exploration of the research on the production of alternative energy is getting catchy as it also reduces the reliability for us in depending on nonrenewable energy like usual fossil fuel. Energy from biomethane production has proven can be obtained by the pretreatment of MSW using hydro-mechanically process. It is recommended to have the hydrothermal (HT) process condition to optimize biocarbon recovery and HT process water (HTPW) biomethane generation in the AD process [35]. In order to further improve bioenergy production, the most advantageous alkaline HT method for maximization of biocarbon production as well as its AD favorable alkaline HT process water (AHTPW) for good biomethane generation have been identified and optimized. The optimal SW composition for anaerobic co-digestion with (a) mechanically treated SW, (b) HTPW, and (c) AHTPW were identified.

Agricultural residues, grass, energy crops, forest residues, and wood are examples of lignocellulosic biomass (LB) [36] (Fig. 5.9). Most of the LBs are comprised of hemicellulose (23–32%), cellulose (38–50%), and lignin (10–25%) [35]. Cellulose is a crystalline substance, whereas hemicellulose is a complex structure composed of different carbohydrate polymers (polysaccharides) [37]. Lignocellulosic waste such as corn residue and municipal food waste are the typical lignocellulosic waste which are commonly being consumed in the cycling process of the generation for bioproduct [36] (Figs. 5.10 and 5.11).

Fig. 5.9 Main waste categories: agricultural waste (straw seeds, cashew nutshells, corn seeds, olive kernels, miscanthus pellets); industrial waste (plastic, electric cable shredder, tires, densified plastic waste, etc.); timber industry waste (charcoal, bark, wood chips, bamboo, salix) [36]

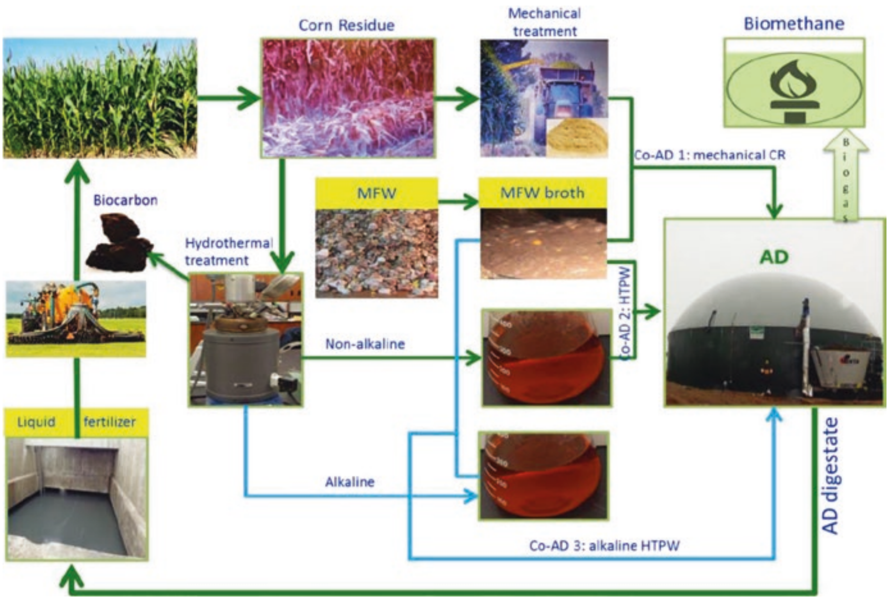


Fig. 5.10 Corn residue and municipal food waste process cycle to generate bioproduct [36]

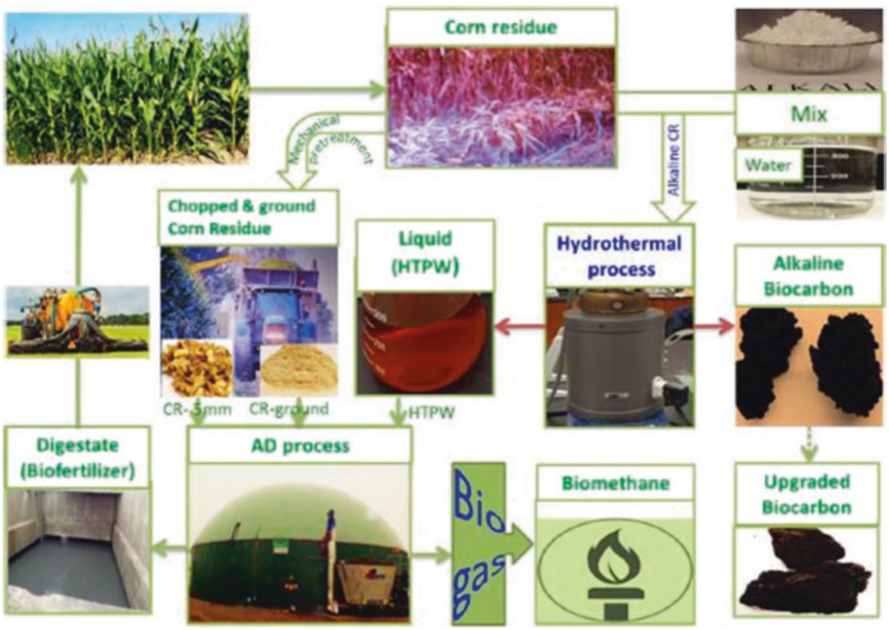


Fig. 5.11 Flowchart of typical conversion of corn residue industry [34]

5.3.3 Pretreatment for MSW

The abundance of LB in MSW need to be fully utilized, but the biggest challenges are to breakdown of the LB's structure. Lignocellulosic biomass needs to undergo pretreatment to suit the requirement of enzymatic conversion; thus, it will lead to a high yield [38]. According on the design scenario of the national renewable energy laboratory (NREL), pretreatment is the largest contribution in the entire cellulose ethanol production expenses, in a study by Lynd [39]. The pretreatment methods are divided into (a) mechanical, physical, (b) chemical, and (c) biological. The simplest but the expensive approach is using physical pretreatments. The energy needed is huge due to the employment of the mechanical machine to decrease feedstock unit volume. Meanwhile, chemical pre-treatments use various chemicals, including acids, alkalis, organic solvents, oxidizing agents, supercritical fluids, and ligninase enzymes. Dilute acid pretreatment, ammonia fiber explosion (AFEX), and lime pretreatment are the best approaches, and they all produce significant and beneficial results. On the other hand, hydrothermal pretreatment is the process of pre-treating biomass with water. Using hydrothermal in pretreatment saves money because it eliminates the need for purchased acid for non-corrosive reactor materials and reduces feedstock size [40].

Pretreatment aims to diminish cellulose crystallinity, promote porosity, and destabilize lignin and hemicellulose (80%), hence able to maximize lignocellulosic pretreatment efficiency [41], pretreatment ought to not neglect these requirements:

1. enhance sugar formation or enzymatic hydrolysis sugar formation
2. avoid carbohydrate degradation
3. try to discard the formation of byproducts inhibitory as much as possible to the subsequent hydrolysis and fermentation processes
4. should be cost-friendly and cost-effective

Without pretreatment, hydrolysis yields are often less than 20% of theoretical yields, whereas pretreatment yields often surpass 90% of theoretical yields. Pretreatments are being created that are chemical, physical, biological, or combinations. The comparison of different treatments is shown in Table 5.9.

5.3.3.1 Mechanical Comminution

Mechanical comminution is a collection of procedures that include chipping, grinding, milling, or sequence of these processes that are used to decrease the particle size of biomass. The size of the particles and the type of biomass have a significant impact on the amount of electricity required for milling.

Table 5.9 Comparison of the pretreatment process [41]

Feature	Dilute acid	Steam explosion	Ammonia fiber explosion (AFEX)	Liquid hot water
Reactive fiber	Yes	Yes	Yes	Yes
Particle size reduction required	Yes	No	No	no
Hydrolyzate inhibitory	Yes	Yes	No	Slightly
Pentose recovery	Moderate	Low	High	High
Low-cost materials of construction	No	Yes	Yes	Yes
Production of process residues	Yes	No	No	No
Potential for process simplicity	Moderate	High	Moderate	High
Effectiveness at low moisture contents	Moderate	High	Very high	Not known

5.3.3.2 Steam Explosion

This method seems like the most effective pretreatment where clearly because of the low use of chemicals and low energy consumption [42, 43]. The major constituent used to treat the feedstock material is high-pressure steam held at a specific temperature and pressure, followed by fast decompression. The biomass is heated with high-pressure steam for a few minutes and then decompressed explosively to change it physically and chemically. By this method, hemicellulose will be hydrolyzed, solubilization of lignin and the cellulose is made more accessible to cellulase enzymes [44].

5.3.3.3 Liquid Hot Water

Separation of biomass into its constituents is required for complete conversion to the highest value products. Whether steam or liquid water is utilized to fractionate biomass, the special features of hot, compressed liquid water must be exploited. This chemical bond breakage may be facilitated further by the elevated disproportionation of water at higher temperatures. Whereas hemicellulose is substantially deacetylated and depolymerized under such conditions [41], some evidence suggests that glycosidic bond cleavage does not require the presence of hemicellulose-derived organic acids. It is required to follow a mechanism other than acid hydrolysis.

5.3.4 Chemical Pretreatment

5.3.4.1 Dilute Acid Hydrolysis

The dilute acid hydrolysis method was extensively employed for the saccharification of lignocellulosic materials; yet, unswerving saccharification was associated with low yields due to sugar breakdown. Dilute sulfuric acid, dilute nitric acid, dilute hydrochloric acid, dilute phosphoric acid, and peracetic acid are the typical pretreatment approach used. Again, the cost-driven effect that has led the sulfuric acid pretreatment has become the greatest significantly studied because it is inexpensive and effective. Hardwood and softwood, herbaceous crops, agricultural residues, and wastepaper pretreated are among the feedstock materials which presented a promising yield once pretreated by the dilute acid.

5.3.4.2 Alkaline Pretreatment

Alkaline pretreatment techniques are focusing on the delignification processes, with a significant amount of hemicellulose solubilized in the water. The use of sodium hydroxide, or sodium hydroxide in combination with other chemicals such as peroxide, proved a convincing result for the degradation of the lignin after the pretreatments have been reported [41].

From the finding, this approach is best once the feedstock is coming from the agricultural residues and herbaceous crops than on wood materials [45]. Additionally, as Fan et al. [46] and McMillan [41] discovered, the efficiency of pretreatment is also dependent on the lignin content of the materials being treated. Alkaline hydrolysis is thought to occur via saponification of the covalent ester linkages that cross-link xylan hemicelluloses and other components [41].

5.3.5 Wet Oxidation

Wet oxidation is a process in which oxygen is used to oxidize substances liquified in water. Two major reactions take place during the processes: (a) a low-temperature hydrolysis reaction and (b) a high-temperature oxidation reaction. It is required to have particle size around 2 mm in length, while the water is added at a ratio of 1 L to 6 g biomass. By adding a chemical to the mixture (often sodium carbonate), the development of byproducts can be reduced significantly. The vessel is pumped with air to a 12-bar pressure. This pretreatment is done at 195 °C for 10–20 min. Wet oxidation can also be used to fractionate lignocellulosic material by eliminating lignin and solubilizing hemicellulose. Tremendously this method had shown a good degradation of a variety of biomass such as wheat straw, corn stover, sugarcane bagasse, cassava, peanuts, rye, canola, faba beans, and reed during the enzymatic hydrolysis where a high concentration of glucose and xylose were obtained.

The famous usage of wet oxidation is the method to pretreat the straw, reed, and other cereal crop residues which have a dense wax coating containing silica and protein. Wet oxidation benefits hardened biomass such as grape stalk (which contains tannins, a compound that hampers delignification) by up to 50% compared to pretreatment with sulfuric acid (25%) conversion.

5.3.5.1 Acid

Acid pretreatment involves the use of concentrated and diluted acids to break the rigid structure of the lignocellulosic material. The top usage of acid is dilute sulfuric acid (H_2SO_4), with the statistically shown that it is commercially used to pretreat a wide variety of biomass types such as switchgrass, corn stover, spruce (softwood), and poplar. Traditionally, diluted sulfuric acid is commonly used to manufacture furfural by hydrolyzing the hemicellulose to simple sugars (such as xylose), which continues to convert into furfural. Not limited to sulfuric acid, the statistic also shows that the researcher also mainly uses several other acids such as hydrochloric acid (HCl) [47], phosphoric acid (H_3PO_4), and nitric acid (HNO_3) for the pretreatment. Due to its ability to remove hemicellulose, acid pretreatments have been used as parts of overall processes in fractionating the components of lignocellulosic biomass [48]. Acid pretreatment (removal of hemicellulose) followed by alkali pretreatment (removal of lignin) results in relatively pure cellulose.

During the chemical pretreatment commonly, it will consist of the addition of concentrated or diluted acids (usually between 0.2% and 2.5% w/w) to the biomass, followed by constant mixing at certain temperature range (30–210 °C). The efficiency of the hydrolysis process of the sugar will last longer than minutes to hours due to the condition of the pretreatment. There are advantages and disadvantages of the acid treatment onto the biomass for the optimum conditions of operation. A key advantage of acid pretreatment is that a subsequent enzymatic hydrolysis step is sometimes not required, as the acid itself hydrolyzes the biomass to yield fermentable sugars. Hemicellulose and lignin are solubilized with minimal degradation, and the hemicellulose is converted to sugars with acid pretreatment. However, extensive washing and/or a detoxification step is needed to remove the acid before the biological process (fermentation step) takes place. Due to the corrosive nature and toxicity of most acids, an adequate material for the reactor is required in order to withstand the required experimental conditions and corrosiveness of the acids. Another drawback is the production of fermentation inhibitors like furfural and HMF (hydroxymethyl furfural) that reduces the effectiveness of the pretreatment method and further processes.

5.3.5.2 Green Solvent

The usage of ionic liquids (IL) and other solvents for the treatment of lignocellulosic biomass has attracted many researchers to involve with as it tunability of the solvent chemistry and hence the ability to dissolve a wide variety of biomass types. Basically, the ionic liquids are salts (consist of a small anion and a large organic cation), which exist as liquids at room temperature and have a very low vapor pressure. The history of the chemistry for the anion and cation can be tuned to generate a wide variety of liquids that can dissolve several biomass types—corn stover, cotton, bagasse, switchgrass, wheat straw, and woods of different hardness (pine, poplar, eucalyptus, and oak). The properties of IL and similar solvents like low vapor pressure make them more than 99% recoverable in several operations, thus reducing costs of solvent usage. Furthermore, since no toxic products are formed throughout the pretreatment operation and plus IL can be recoverable, the researcher recognized them as green solvents. Table 5.10 (adapted from the work of Sun and coworkers) lists the dissolving capacity of different celluloses by a variety of ILs. For an IL to be used in the pretreatment of biomass, it should not only have high dissolution capacity, but also low melting point, low viscosity, low/no toxicity, and high stability.

Table 5.10 Advantages and disadvantages of different pretreatment methods of lignocellulosic solid waste [38]

Pretreatment method	Advantages	Disadvantage
Alkali	• Efficient removal of lignin	• High cost of an alkaline catalyst
	• Low inhibitor formation	• Alteration of lignin structure
Acid	• High glucose yield	• High costs of acid and need for recovery
	• Solubilize hemicellulose	• High costs of corrosive resistant equipment
		• Formation of inhibition
Green solvents	• Lignin and hemicellulose hydrolysis	• High solvent cost
	• Ability to dissolve high loadings of different biomass type	• Need for solvent recovery and recycle
	• Mild processing condition (low temperature)	
Steam	• Cost-effective	• Partial hemicellulose degradation
	• Lignin transformation and hemicellulose solubilization	• Acid catalyst needed to make the process efficient with high lignin content material
	• High yield of glucose and hemicellulose in a two-step process	• Toxic compound generation
LHW	• Separation nearly pure hemicellulose from rest of feedstock	• High energy/water input
	• No need for a catalyst	• Solid mass left over will need to be dealt with (cellulose/lignin)
	• Hydrolysis of hemicellulose	
AFEX	• Highly effective for herbaceous material and low lignin content biomass	• Recycling of ammonia is needed
	• Cellulose becomes more accessible	• Less effective process with increasing lignin content
	• Causes inactivity between lignin and enzymes	• Alter lignin structure
		• High cost of ammonia
ARP	• Removes majority of lignin	• High energy costs and liquid loading
	• High cellulose content after pretreatment	
	• Herbaceous materials are most affected	

5.4 Developing an Energy from Waste Facility

5.4.1 Thermochemical

This section focuses on the thermochemical waste fuel technology as many conversion procedures (gasification or pyrolysis) demand a uniform feedstock. The technology analysis contains a process description, limits, and current and future applications. Environmental impact, energy balances, material regeneration, and mode of operation are the evaluation criteria (e.g., flexibility in dealing with input variation). Table 5.11 describes the different types of thermochemical treatment for MSW and where it falls under which category of treatment. An advanced thermal conversion system involving high-temperature gasification of biomass and municipal waste into biofuel, syngas, or hydrogen-rich gas is presented in this section. Figure 5.12 depicts the overall pretreatment available for MSW.

5.4.2 Incineration

In comparison to pyrolysis and gasification, incineration has been widely accepted by countries around the world Table 5.12. The concepts of incineration are:

1. to treat waste by reducing the amount of its volume (oxidation of the combustible materials contained in the waste) and hazardous characteristics.
2. to capture or disrupt potentially harmful substances.

Besides that, the incineration processes can be a technology for energy recovery, mineral and/or chemical content of waste. In addition, this technology can be implemented in a wide range of wastes. The property of waste is highly heterogeneous, the composition mainly of organic substances, minerals, metals, and water. During incineration, flue gases are generated that contain most of the available fuel energy as heat. The organic waste substances burn when they have reached the ignition

Table 5.11 Different types of thermochemical treatment for MSW [46]

Type of Thermochemical Treatment	Description
Pyrolysis	Thermal degradation of organic material in the absence of oxygen
Gasification	Partial oxidation
Incineration	Full oxidative combustion
Plasma-based technologies	Combination of (plasma-assisted) pyrolysis/gasification of the organic fraction and plasma vitrification of the inorganic fraction of waste feed
Combination processes	Combination of different thermochemical processes

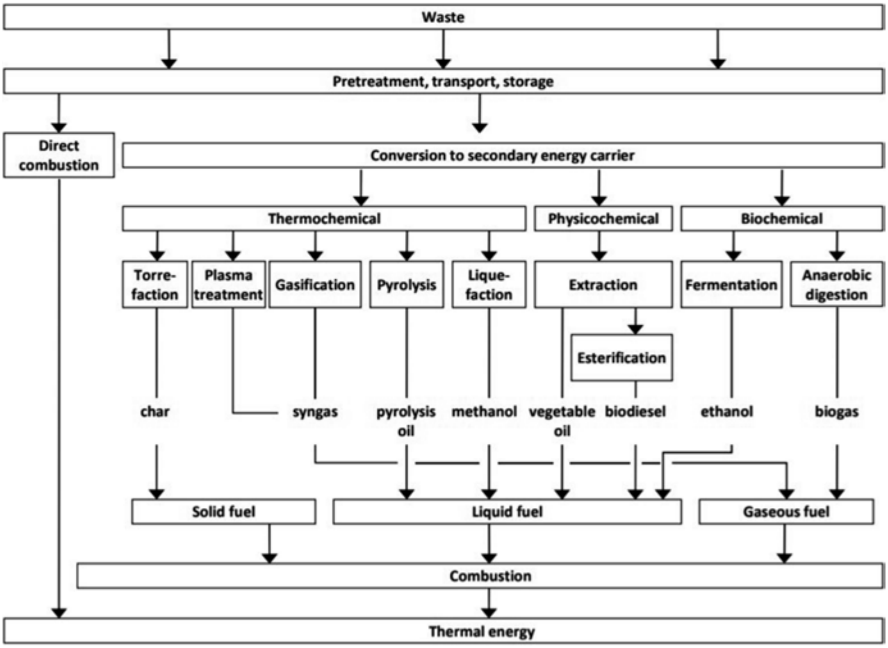


Fig. 5.12 Overall of the pretreatment of the MSW [46]

Table 5.12 Typical reaction conditions and products from pyrolysis, gasification, and incineration processes [46]

	Pyrolysis	Gasification	Combustion	Plasma treatment
Temperature	250–900	500–1800	800–1450	1200–2000
Pressure (bar)	1	1–45	1	1
Atmosphere	Inert/nitrogen	Gasification agent: O_2, H_2O	Air	Gasification agent: O_2, H_2O Plasma gas: O_2, N_2, Ar
Stoichiometry ratio	0	<1	>1	<1
Product from the process				
Gas phase	H_2, CO, H_2O, N_2,	H_2, CO, CO_2	CO_2, H_2O, O_2, N_2	H_2, CO, CO_2
Solid phase	Hydrocarbons	CH_4, H_2O, N_2	Slag, ash	CH_4, H_2O, N_2
Liquid phase	Cole, ash	Slag, ash		Slag, ash
	Pyrolysis oil			
	Water			

temperature and encounter oxygen. The actual combustion process takes place in the gas phase in fractions of seconds and simultaneously releases energy.

Figure 5.13 shows the flow diagram of WtE—from MSW to electricity through incineration.

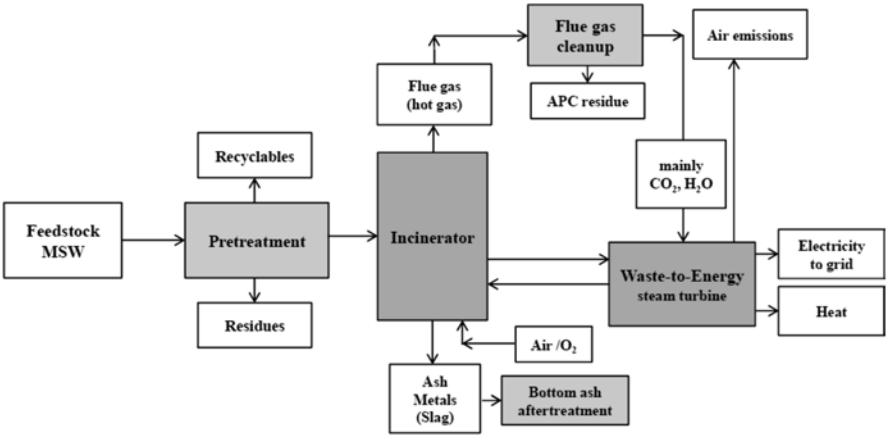


Fig. 5.13 WtE—from MSW to electricity through incineration (APC stands for Air Pollution Control) [49]

5.4.3 *Gasification*

The other technology that falls under thermochemical is the gasification method. Gasification includes converting carbon-based compounds into a flammable gas (synthesis gas or syngas). The process takes place at a high temperature (500–1800 °C or higher) where several reactions between carbonaceous materials with air, oxygen, steam, carbon dioxide, and/or a mixture of these gases occur. Air gasification produces a low heating value (LHV) gas (4–7 MJ/Nm^3 higher heating value), while oxygen gasification produces a medium heating value (MHV) gas (10–18 MJ/Nm^3 higher heating value) [50]. The syngas contains CO_2, CO, H_2, CH_4, H_2O, trace amounts of higher hydrocarbons, inert gases originating from the gasification agent, various contaminants such as small char particles, ash, and tars [51]. A second-generation liquid biofuel can be made from syngas, which can be utilized to produce electricity and/or heat more efficiently. The gasification advantages presented in Fig. 5.14 while Fig. 5.15 illustrates the flow diagram of WtE—from MSW to electricity through gasification.

5.4.4 *Pyrolysis*

Pyrolysis is thermal degradation (400–900 °C, but usually lower than 700 °C) either in the complete absence of an oxidizing agent or with such a limited supply that gasification does not occur to an appreciable extent (described as partial gasification) and is used to provide the thermal energy required for pyrolysis at the expense of product yields. Products from pyrolysis exhibit in Fig. 5.16 which the relative

Fig. 5.14 Advantages of gasification technology

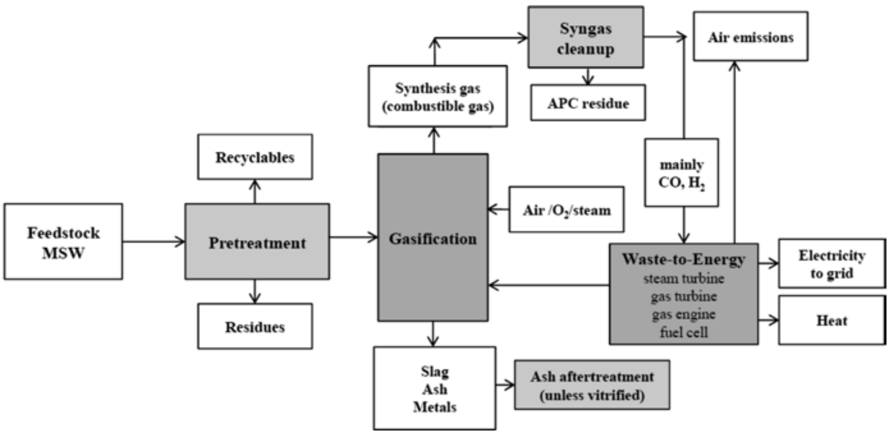
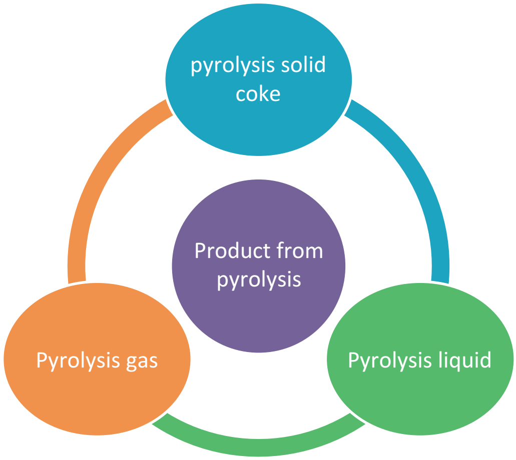


Fig. 5.15 WtE—from MSW to electricity through gasification [49]

Fig. 5.16 Three products from pyrolysis



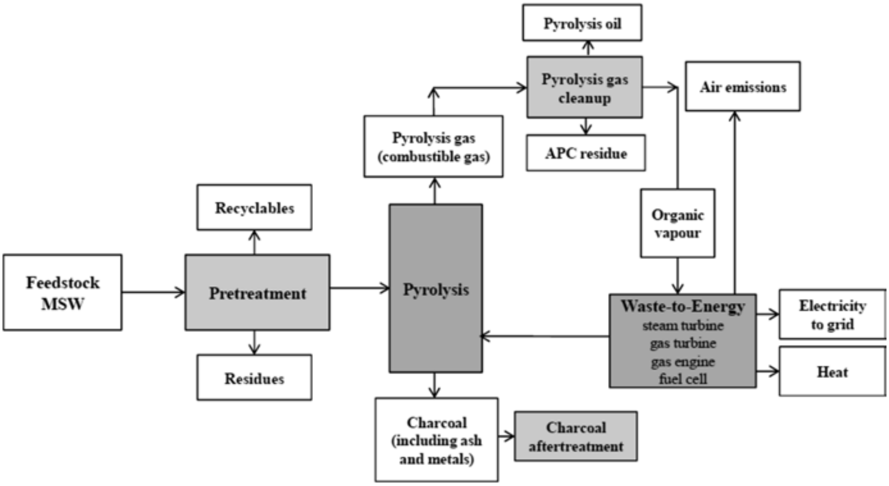


Fig. 5.17 WtE—from MSW to electricity through pyrolysis [49]

proportions of which depend very much on the pyrolysis method and reactor process parameters.

For MSW, the heating values of pyrolysis gas are typically between 5 and 15 MJ/m^3, while for RDF, the values are typically between 15 and 30 MJ/m^3 [51]. MSW to electricity process through pyrolysis process is shown in Fig. 5.17. Figure 5.18 depicts the basic pyrolysis process stages flow waste treatment.

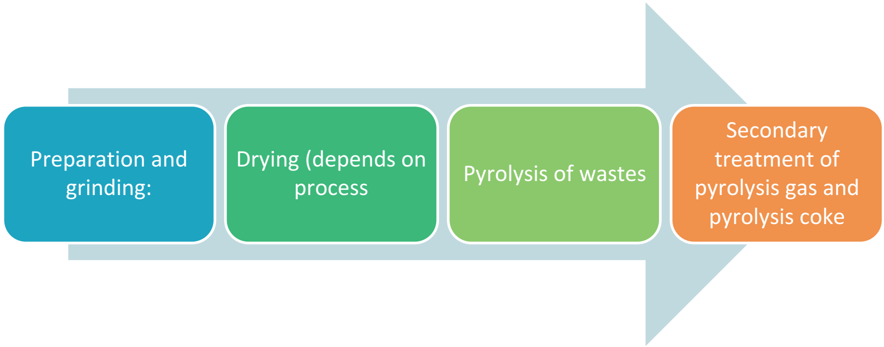


Fig. 5.18 Basic process stages flow

5.4.5 Combination Processes

In the following subsections, we will look at a small number of different combinations of procedures.

5.4.5.1 Combination Pyrolisis-Gasification

In this section, two distinct types of pyrolysis-gasification combinations are discussed as different stages and processes that are directly connected. On most occasions, the waste must be dried and shredded before attempting to enter the first thermal phase. After pyrolysis, the metals and, if necessary, inert material may be discarded. Since pyrolysis gas and pyrolysis coke demand reheating during the gasification process, the technical and energy necessities are greater than for processes that are directly connected. Pyrolysis coke is decommissioned in two stages, with the first stage supplying gas to the second thermal stage, which is an entrained flow gasifier. On this level, both (metals and inert materials) can be removed from the pyrolytic coke. Pyrolysis gas is subsequently sent into the second thermal stage, which is an entrenched flux gasifier, coupled with the pyrolysis oil and the fine, solid fraction. During the entrained flow, at high pressure and at a temperature of 1300 °C, the oil and fine fraction are gasified, releasing carbon dioxide. To recover energy, the synthesis gas produced is cleaned and then combusted. Using a water bath, the solid remnants are melted down and filtered out, eliminating any remaining residue [51].

5.4.5.2 Combination Gasification-Combustion

The use of a fluidized bed gasifier in combination with a high-temperature combustor can result in the melting of ash. Shredding wastes, waste plastics, and MSW are gasified at a temperature of roughly 580 °C in an internally circulating bubbling fluidized bed. The material that is enormous in size is separated from the bed material at the bottom of the pile of material. The material from the bed is recycled back into the gasifier. In contrast, for fine ash, small char particles and flammable gas are delivered to the cyclonic ash melting chamber (to which air is injected to produce the desired temperature for ash melting, which is generally around 1350–1450 °C). The ash melting chamber is an integral feature of the steam boiler that is utilized for energy recovery. There are a number of other products produced by this method, including ferrous and nonferrous recyclable metals, a vitrified slag (which has reduced leaching hazards) and metal concentrates made from secondary ash, in addition to the power and steam.

When compared to other gasification processes, this one is clearly performed at atmospheric pressure and with the use of air (not rely on oxygen). Pretreatment of MSW with shredding is required in order to reduce the particle size to 300 mm in diameter. Wastes that already meet this criterion can be processed without the need for shredding. In addition to MSW, other wastes such as sewage sludge, bone meal, clinical waste, industrial slag and sludge are handled in the various plants currently in operation [52].

5.4.6 Plasma-Based Technologies

Plasma is referred to as the fourth state of matter since it exists in four different states at the same time. Because plasma is highly reactive, it behaves in a manner that is significantly different from that of ordinary gases, solids, or liquids. The formation of plasma comes from the process of gaseous molecules are forced into high energy collisions with charged electrons, resulting in the generation of charged particles. There are two energies required to create plasma either (1) through thermal or (2) carried by either an electric current or electromagnetic radiation. It is possible to distinguish two main groups of plasmas based on the energy source used and the conditions under which they are generated. The first is high-temperature plasmas, also known as fusion plasmas, in which all species are in a thermodynamic equilibrium state, and the second is low-temperature plasmas, also known as gas discharges [53]. This technology is quite new and at the emerging stage for the waste management. Overall, the primary advantages of the plasma it offers for waste treatment processes are high energy intensities and high temperatures: Fig. 5.19 shows the advantages of plasma's process in WtE.

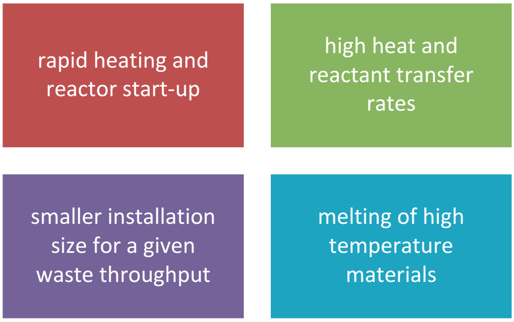


Fig. 5.19 Plasma's advantages

5.4.7 Biochemical

5.4.7.1 Introduction

It is well known that abundant municipal solid waste (MSW) is an emerging biomass source where it can become the highest potential for large-scale second-generation bioethanol production. The biochemical process describes an efficient MSW to ethanol bioconversion process that comprises pretreatment and enzymatic hydrolysis, as well as precise quantitative information on the settings that maximize the glucose production to 80% following a 24-h hydrolysis reaction. In the biochemical conversion process, solid biomass waste is converted to ethanol by sequential steps of pretreatment (to reduce the recalcitrance of biomass), hydrolysis (conversion of sugar polymers to monomers), and fermentation (sugars to ethanol). Feedstocks were pretreated using three chemical pretreatments (dilute acid, dilute alkali, and hot water) and subsequently hydrolyzed enzymatically to investigate the effect of pretreatment and estimate the potential ethanol yields. Carbohydrate content in biomass is varied depending on the maximum cellulose content. All pretreatments are effective in increasing the hydrolysis yields and bioethanol yield. Besides that, the potential of this simplified compound also can contribute to the energy via the anaerobic process through the methanogenesis process, thus allowing the generation of methane gas.

5.4.7.2 Fermentation: Ethanol Production

Figure 5.20 introduces a fermentation flow diagram for methane production from municipal solid waste (MSW).

This method can be separated into two steps with a focus on the enzyme hydrolysis process: long chains are hydrolyzed into soluble oligomers during the first stage and soluble oligomers are degraded into sugar monomers throughout the hydrolysis process. Several experiments revealed that some of the primary parameters important for limiting hydrolysis rate because of effects on enzyme binding and substrate access to cellulase enzymes include the physical property of cellulose such as crystallinity, degree of polymerization, and accessible surface area [54]. The

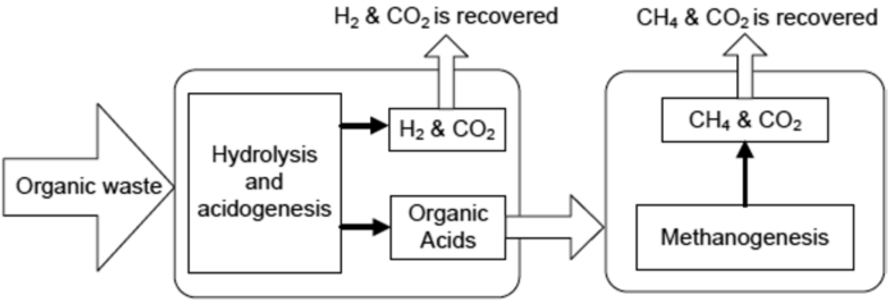


Fig. 5.20 Fermentation and methane production from MSW

Table 5.13 Mode of action of enzymatic hydrolysis of cellulose by an enzyme from various classes during the fermentation and anaerobic process of lignocellulosic biomass from MSW [41]

Enzyme class	Mode of action
Endo-cellulase (EG, Non-processive with CBM)	• Carbohydrate binding module (CBM) binds to surface chains randomly and breaks bonds at catalytic domain (CD)
Endo-cellulase (EG, Non-processive without CBM)	• Breaks bonds on surface chains in a random pattern
Endo-cellulase (EG, Processive with CBM)	• CBM binds to surface chains randomly and breaks bond at CD
	• Enzyme moves along the chain (towards non-reducing end or reducing end) and cut every alternate bond releasing cellobiose until a minimum chain length is achieved
Exo-cellulase (CBH I, Processive)	• CBM attaches from non-reducing end on surface chains and pull the chain toward CD
	• Chain passes through CD (tunnel luke shape) and every alternate bind is broken to produce cellobiose
	• Enzyme moves along the chain (towards non-reducing end) and cut every alternate bond until a minimum chain length is reached
Exo-cellulase (CBH I, Non-Processive)	• Attack from reducing end on surface chains and cut every alternate bond to produce cellobiose
Exo-cellulase (CBH II, Processive)	• CBM attaches from non-reducing end on surface chains and pull the chin toward CD
	• Chain passes through the tunnel shaped CD and every alternate bond is broken to produce cellobiose.
	• Enzyme moves along the chain (towards reducing end) and cuts every alternate bond until a minimum chain length is reached
Exo-cellulase (CBH II, Non-Processive)	• Attack from reducing end on surface chains and cut every alternate bond to produce cellobiose
B-glucosidase	• Act on cellobiose and soluble oligomers (DP $\leq$ 6) and produce glucose by breaking bond

hydrolysis of cellulose is influenced by the crystalline system as the glycoside linkages are difficult to hydrolyze in crystalline regions as compared with in amorphous parts [54]. The mode of the enzymatic hydrolysis on cellulose from various classes mode of an enzyme is presented in Table 5.13. Thus, from here, the simplified

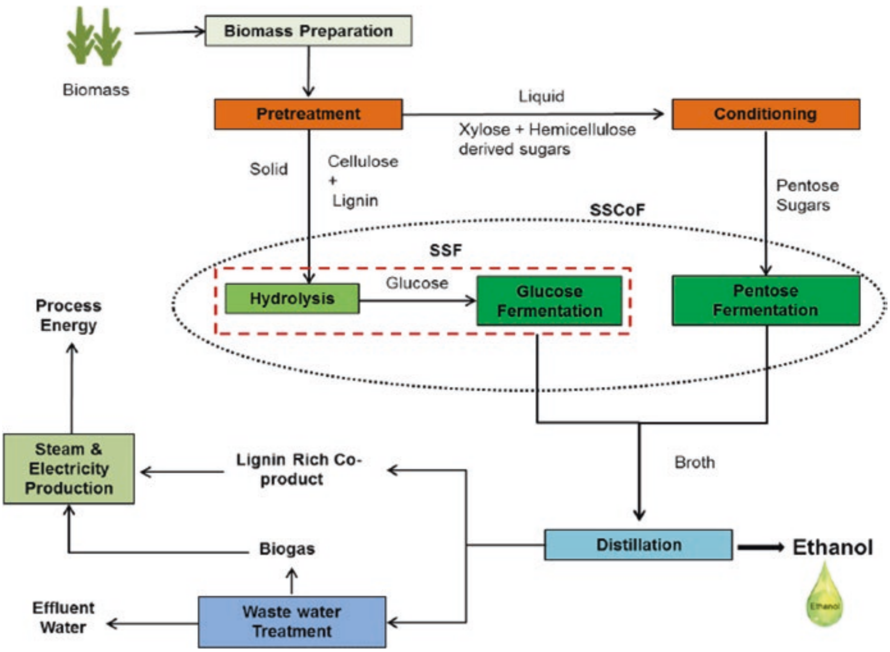


Fig. 5.21 Generic process of bioethanol production from lignocellulosic waste from MSW

compound also can go toward the process of fermentation for bioethanol production (commonly using commercial yeast). The yeast will have enough supply of "food" as all the enzyme modes are functioning well; thus, the solid waste becomes very rich in nutrients and reflects the rapid growth of yeast. This reflects a higher biomass conversion to become new renewable energy, biofuel (bioethanol) (Figs. 5.21 and 5.22).

5.5 Reducing the Environmental Impacts and Maximizing the Energy

Climate change is the most severe environmental risk facing mankind and the world. Human activity is the source of the greenhouse gases that cause it. Carbon dioxide (CO_2) is the most significant of these pollutants since it raises average temperatures at the Earth's surface, resulting in more severe weather events such as floods, droughts, and hurricanes, as well as increasing sea levels and damage to whole ecosystems. If we do not act quickly, the consequences for people all over the world may be disastrous.

To prevent harmful climate change, we must reduce CO_2 emissions globally over the next decade. We need to turn to sources of energy that do not emit CO_2—and

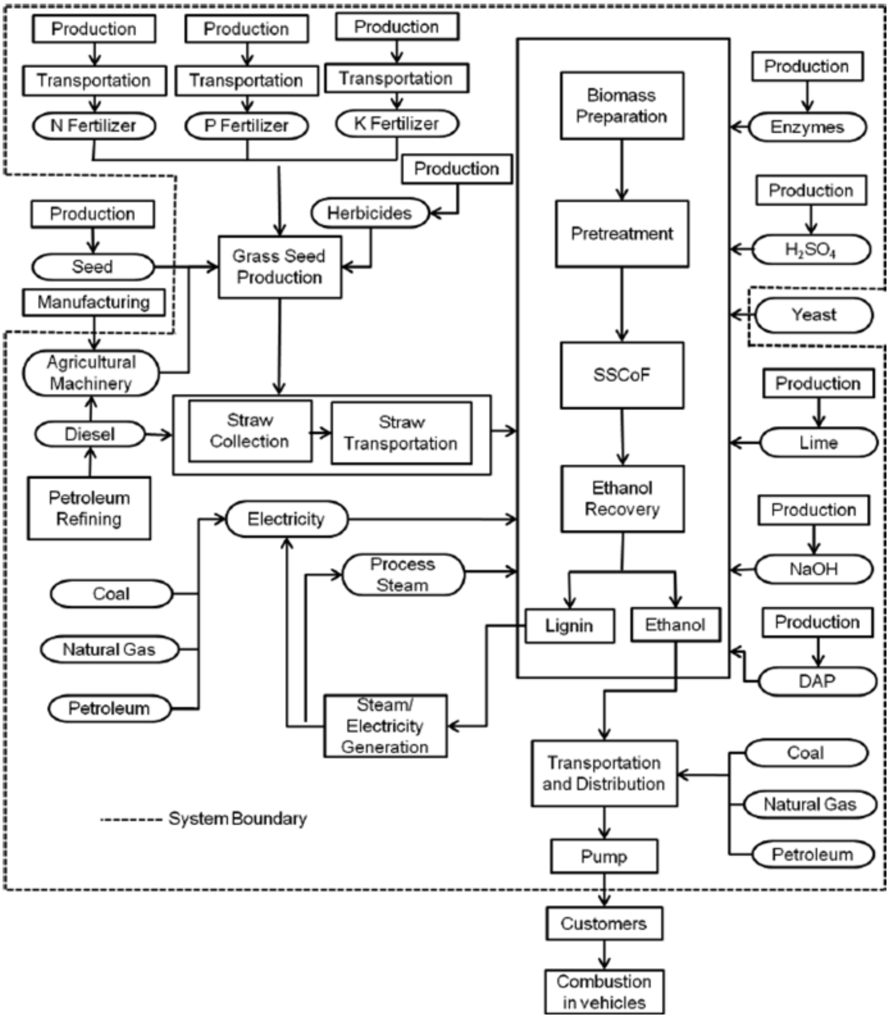


Fig. 5.22 Process flow diagram of bioethanol production from lignocellulosic waste (grass straw) from MSW

there are plenty of them—in addition to doing whatever we can to conserve and use energy more efficiently. Renewable energy is derived from non-depleting sources such as the sun, wind, tides, waves, and plants. These renewable energy sources can be used to produce electricity without releasing carbon dioxide into the atmosphere. For example, the United Kingdom has committed to obtaining 20% of all energy (not only electricity but also heat and transportation fuel) from renewable sources by 2020. The United Kingdom's contribution to this goal is 15%. We still have a long way to go to achieve this goal: green energy accounted for less than 2% of total UK energy in 2006.

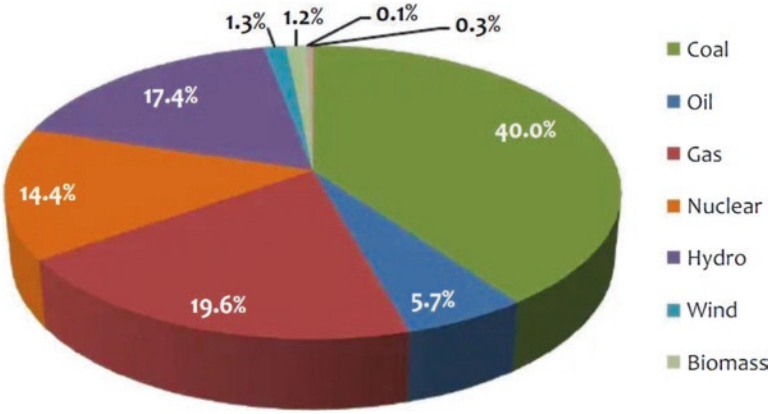


Fig. 5.23 Shares of energy sources used in electricity production 2007 [4]. (Reuse by permission from Elsevier and Copyright Clearance Center)

As it is vital for the widespread use of fossil fuels, the primary source of many environmental pressures, a substantial amount of the fuels will be exhausted in the future. Thus, it appears as if a transition to renewable energy sources is needed. One downside to renewable energy is that it requires property, which is significant. But, for those who can deal with the investment in infrastructure, renewable energy is attractive. Environmental effects are not any more than earlier in the life cycle, in the building of the power plants, to be sure, but more important. To this end, on a note, one point, the justification for developing life cycle evaluation is that it is to do cost/reserve analysis such as to compare renewables with fossil power plants is to analyze trade-offs. The amount of work that has been done on the LCAs has focused on various renewable power technologies pales in comparison to that how many were done in the past.

The overall human population is increasing, but there are places where it is slower and places where it is accelerating, leading to a rise in energy demand. By 2035, it is expected that renewable sources will produce 66% percent of the electricity. This is because the majority of the world's energy is nonrenewable, as shown in Fig. 5.23, according to [4].

Although energy is mainly used for heat and electricity, it can also be transformed into other ways. While the overall purpose of his work is to assess the environmental effect of renewable energy, only analyzing the output of electricity provides a consistent reference. Furthermore, as one of the most readily available and flexible electricity carriers today, it is gaining a larger market share in energy initiatives and scoring higher growth measures [4].

Resources such as fossil fuels and nuclear ores can be depleted at a pace that is millions of years for every year, which means they are now being consumed more rapidly than they can be replenished. This explains why there is a limited supply of non-capacity of nonrenewable energy, and hence why alternative energy sources must be used until they are not fixed or built-in if nonrenewable resources are depleted. Nations have turned their attention to rising energy efficiency as well as to renewable energy to address energy insecurity issues, the majority of which is related to climate change.

No fossil fuel reserves mean countries benefit from having higher energy security and clean energy solutions because these renewable resources are known to be fully environmentally friendly [55]. Renewable energy supporters, on the other hand, believe that this low-density, low-efficiency technologies will never be viable. Scientists have also often contended that the low output of fossil fuels such as coal and nuclear are not competing with renewable energy sources such as solar and hydroelectric.

The desire to increase the environmental efficiency of energy systems is unquestionable, but whether renewable systems are superior to nonrenewable systems must be resolved. Since they produce less greenhouse gases than conventional energy, renewable energy technologies are praised for their capability of supplying abundant amounts of power. This factor should also be factored into future studies: on the many instances where natural and artificial causes are blamed for a wide-ranging environmental impact, including ozone depletion, acid rain, toxins and carcinogens, as well as lesser impacts such as habitat degradation, consequently, we also need to examine more environmental variables in depth. So, energy is being used at an exponential rate and accelerating; it is imperative that energy policymakers have a profound understanding of the total consequences of the implementation of new technology.

The whole scientific community is commonly agreeing that bio componence is renewable energy. This fertilizer will cause the plant to emit a significant amount of CO_2 throughout its cycle, which will be offset by CO_2 it takes over the life of the course of the plant to grow biomass. According to some research, it appears that removing all that vegetation results in more carbon storage, such as carbon sequestration, than that achieved with the addition of more vegetation. Furthermore, the decomposition of the vast carbon contained in wood occurs in the short time that it takes for trees to die and be decomposed, which causes much more global warming than a longer period of which could result in the release of more carbon. Organic matter emits only about half the sulfur dioxide as carbon dioxide when combusted, so organic combustors have lower sulfur dioxide emissions than their fossil fuel alternatives.

Biomass may be transformed into various forms of energy; it may be combusted, such as hydrocarbon or gaseous, or it may be converted to aqueous or to liquid or gaseous fuels. For thousands of years, traditional biomass use has included the use of biomass for space heating and cooking. Due to this, there is a significant amount of air pollution as wood is used in open air, there is a concern with the abundance of air emissions from pits and fireplaces in undeveloped regions. Particulates, volatile organic compounds (such as benzene, toluene, and *t*-butyl hydroperoxide), and dioxins, which are produced when incomplete combustion occurs in the contaminants (for example, due to either gas leakage or breakdown) [56]. More recently, these contaminants have become of environmental as well as health importance due to the lack of pollution controls.

Simultaneously, most of the municipal solid waste is made up of biodegradable components, such as food wastes, paper wastes, and yard wastes. These wastes are treated using a specially designed furnace, which simultaneously dries and burns them at the same time. The primary objective of a power plant is to produce steam, which is then used to drive a turbine, which generates electricity. Most municipalities are not significantly benefited from dealing with their solid waste because solid waste management has the additional advantage of sequestration, which makes it not increase their total power use, not to mention the conservation of energy.

Biomass can be converted into liquid fuel, which yields ethanol as a byproduct. More ethanol will be produced by fermenting biomass in the form of carbon-rich materials such as animal wastes, or dung in the anaerobic decomposition process. Before the ethanol can be used in engines, it must be separated from water and dried. Conventional fossil fuel, that is, gasoline, is widely used with biomethane to maximize fuel efficiency and minimize the effect on the atmosphere, a mixture of bioethanol and biomethane, to maximize the fuel and minimize the environment. Bioethanol has been added to the petrol, making the whole mixture more combustible, increasing oxygen content, thereby making it easier to combust completely and cutting down on CO_2 emissions.

Anaerobic degradation of industrial sludges, crops, animal waste, and domestic sewage may generate biogas and *digestate that can be used as fertilizer. Carbon (carbon dioxide is the majority) and methane (CH_4)* are the three components of natural gas. They may also be present, including a few different elements, as well as ammonia and sulfides. Therefore, the chemical composition of the biomass and the digestibility of the biomass would influence the ratio of methane to carbon dioxide in the two gases that are formed.

Using waste as a base for biogas or biomass combustion plants will result in even more greenhouse gas (GHG) reductions. The reduction of GHG emissions aids in the stabilization of the global environment. As a result, biogas and biomass combustion processes provide a significant advantage over fossil-fuel-based energy production. The cleaning and sanitation effect of biogas plants has significant positive environmental and health effects. Fermentation eliminates odors and allows the substrate to be treated more easily. Biogas technology will save money in the medical sector and improve people's health by virtue of this sanitation impact. Another significant environmental effect may be caused by biomass transportation. External consequences of transportation include air pollution and noise. This negative effect should be held to a minimum for environmental and social purposes.

5.6 Recovery Energy from Waste: Global Development

The world's population is rapidly urbanizing and industrializing, posing substantial challenges such as escalating energy demand, massive waste production, and environmental degradation. The waste-to-energy nexus created on the 5R concept (Reduce, Reuse, Recycle, Recovery, and Restore) is crucial in unraveling these

Gordian knots. Socioeconomic development has caused a rise in solid waste production. Most municipal solid wastes (MSW) are non-biodegradable and take longer to degrade into natural compounds. MSW includes organic matter, plastics, metals, glasses, textiles, wood, rubber, leather, and paper, all of which come from domestic, commercial, or industrial sources [57]. The rate of waste produced in different countries around the world has been influenced by economic conditions and living standards. The sharp rise in MSW per person from 0.5 to 1.7 kg shows the gravity of the situation. Undeniably, around the world, the rate of waste accumulation is outpacing the rate of suburbanization. Annual MSW output is currently around 1.3 billion tons or about 1.2 kg/person/day. This figure is projected to reach 2.2 billion tons by 2025, or 1.42 kg/capita/day [58]. MSW output is estimated to achieve 9.5 billion tons by 2050 [59].

In developing countries like India, MSW generation is increasing at a rate of 1.3%/year, suggesting an increase in public socioeconomic standards. India currently produces about 90 million tons of MSW per year, with per capita waste generation estimated at 0.37 kg/day [60]. Furthermore, nearly 94% of waste is thrown out perilously in open dumps with no segregation, with 70–75% of it being organic matter [61]. In 2016, China, the world's most populous nation, generated 234 million tons of MSW [47]. MSW generation rates are 1.34 kg/capita/day, 2.13 kg/capita/day, 2.00 kg/capita/day, 0.09 kg/capita/day, and 0.58 kg/capita/day in the United Kingdom, the United States, South Africa, Ghana, and Nigeria, respectively [48].

Agriculture is important to the global economy, contributing 33% of the global GDP and employing 26.81% of the global workforce, with agricultural land accounting for 38.14% of all land [62]. Residues from farming fields, animal waste, and agro-industrial effluent are all examples of agricultural waste. Over 3 billion tons of agricultural waste are produced annually around the world, with India producing more than 600 million tons [62]. Besides the panicle residue after harvest, rice grains contain >50% non-edible biomass, including roots, blades, and sheaths. Rice straw is grown worldwide in approximately 731 million tons, and 126.6 million tons are produced in India alone.

The Electricity Act of 2003 was passed in India's parliament, stressing the importance of rapid electrification of un-electrified villages. Owing to economic restrictions and difficult terrain, supplying energy from large coal-fired power plants is not always feasible. Furthermore, the number of customers in many places is extremely low. As a result, electrifying these villages with grid power is not cost-effective. In such areas, solar power is more significant. The Jawaharlal Nehru National Solar Power Mission was established as a result, with the aim of installing 20,000 MW of solar power by 2022 and reaching grid parity by the same year. As a result, solar power output in India is driven by international standards requiring a lower carbon footprint and rapid rural electrification. Different Indian states have implemented solar energy policies based on supply convenience and other socioeconomic factors in accordance with national policy.

Aside from rural electrification, the Indian government has implemented a range of policies to establish renewable energy policies to meet international carbon emission reduction commitments. Furthermore, small and un-electrified villages in India are not suitable for grid electrification due to poor economic conditions and difficult terrain. As a result, policymakers started to think about distributed generation using local resources. Until now, thermal power from large coal-fired power plants dominated the Indian power sector. The share of power generated by various resources in the Indian grid is depicted in Fig. 5.24.

Jamaica's energy requirements, on the other hand, are largely dependent on imported petroleum. Around 91% of the country's electricity is imported, with the rest coming from renewable sources. The rising cost of global oil, combined with the local necessity for fuel and a shortage of monetary resources to finance an ever-escalating oil bill, forces Jamaica to investigate alternative energy sources as soon as possible. In its National Energy Policy 2009–2030 and Vision 2030 Jamaica—National Development Plan, Jamaica is setting goals for renewable energy (20% by 2030) and energy supply diversification (70% by 2030). The National Energy from Waste Policy will assist in achieving these goals.

Jamaica outperforms most Caribbean countries in terms of renewable energy production. Wind, small hydro, solar, and biomass (primarily fuelwood, sugar cane ethanol used in E10, and bagasse used in cogeneration facilities) account for 9% of the country's energy mix. The involvement of various sources in the total amount of renewable energy is depicted in Fig. 5.25. Bagasse, a sugar cane waste product, accounts for more than a third of the country's renewable energy sources. Utilizing a variability of technologies, such as municipal solid waste incineration, landfill gas capture, biodiesel production, biogas production from animal waste, and wastewater sludge production, Jamaica may increase its contribution and expand energy-from-waste projects based on other types of waste. This policy establishes the foundation for further research, growth, and expansion of these possibilities.

In China, public-private partnership (PPP) waste-to-energy (WTE) incineration has seen instant development to manage sustainably and effectively due to the increase in the amount of municipal solid waste (MSW). After the execution of China's "Reform and Opening" policy in 1978, several significant economic and social milestones have been achieved. In 2019, China overtook the United States as the world's second-largest economy, with a GDP of CNY 99,086.5 billion (USD

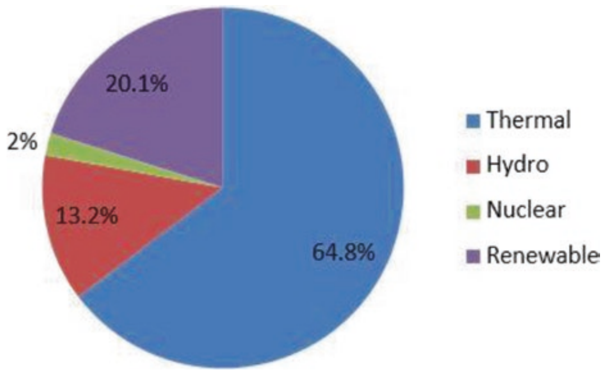
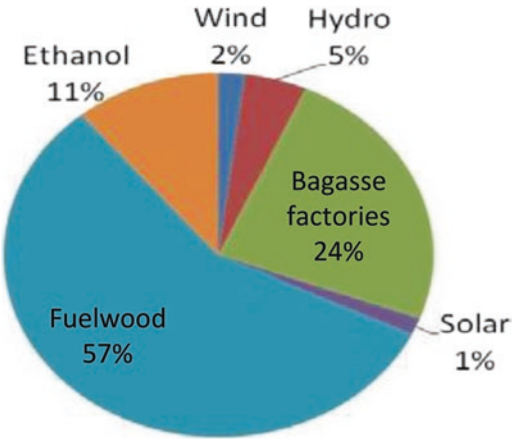


Fig. 5.24 Share of different energy sources in electricity generation in India

Fig. 5.25 Contribution of different sources for renewable energy in Jamaica



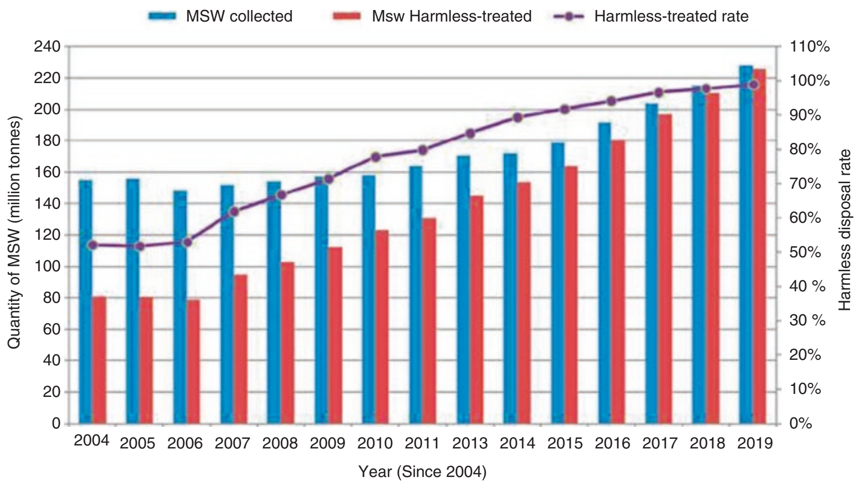


Fig. 5.26 MSW collection and treatment in China [63]. Reuse by permission from Elsevier and Copyright Clearance Center

14,015.1 billion) and a per capita GDP of CNY 70,892 (USD 10,027). A rising number of people have been moving from rural to urban areas because of the country's rapid industrialization, resulting in an ever-increasing urbanization trend. At the end of 2019, China's total urban population was 848.43 million, representing a 60.6% urbanization rate [63].

MSW generation has increased significantly because of prompt industrial development and suburbanization, as well as shifts in expenditure patterns because of rising living standards. According to the Asian Development Bank, China is the world's second-largest producer of MSW. The annual volume of MSW increased from 155.1 to 228.0 million metric tons, as shown in Fig. 5.26 (an annual rate of

3.1%) between 2004 and 2018, while the annual number of harmless-treated MSW increased from 80.9 to 225.7 million metric tons (an annual rate of 11.9%).

Even though China's annual MSW volume is less than that of the United States, its growth rate is significantly higher. According to Cui et al. [63], China's average annual MSW growth rate is 6.2%, while the USA's is just 1%, meaning that China will overtake the USA as the world's largest MSW generator by 2021. Meanwhile, China's MSW production per capita is less than a third of that of the United States and even less than that of other Asian countries, implying that China's MSW output will increase.

Additionally, as the economies of the EU's member states expand, the EU must resolve waste generation issues. With 392 million tons of urban solid waste, the EU is officially ranked second in the world [64]. Over the last two decades, the production of municipal solid waste in the EU has gradually increased [65]. In 2014, the EU initiated the Seventh Environmental Action Plan (EAP) to promote a circular economy and decrease the adverse impact of urban waste on the environment. According to the EAP, reducing solid waste to at least 65% of current levels would help the 2030 target of "zero waste emissions" be met.

Since technology helps reduce pollution, it necessitates the use of more resources (including production factors) and electricity. Because of technical solutions, filters or dilution may result in waste. As a result, the rate of recovery is slow, even though most of the waste generated in the EU is managed using various technologies. Meanwhile, waste generation is regarded as a critical factor in the renewable energy-economic growth nexus. However, current waste-to-energy plants perform poorly in terms of heat recovery, and efficient incineration capacity in the EU is regionally concentrated [66].

Material life spans are shortening as technological advancement accelerates, resulting in increased waste generation. The toxicity of mobile phone waste, for example, has ascended because of technological advances. This has yielded several positive outcomes, such as the production of recycled materials and boosted energy usage. However, novel recycling strategies must be established to address a variety of waste sources and landfills. Prior research has established the critical role of R&D capabilities in boosting economic growth [67]. In the BRICS countries, for example, increased R&D intensity helped to decouple economic growth from CO_2 emissions.

The current study by [66] adds to the growing body of evidence that urban waste generation and economic development have a long-run equilibrium relationship. The long-term bidirectional connection exists between municipal waste production and R&D rate, as well as municipal waste production and heating energy performance. For regions of former EU member states, there was a positive bidirectional causal relationship between municipal waste generation and GDP, but for regions of new EU member states, there was only a unidirectional long-run effect running from GDP to municipal waste generation. These findings suggest that in the short term, bidirectional causality exists for both types of regions. These results, taken together, illustrate the importance of decentralized waste policies and have significant consequences for national and regional policymakers.

Every year, tens of thousands of waste management facilities are planned and constructed throughout the United States. The US Environmental Protection Agency (USEPA) reports that well over $100 billion is spent on environmental protection per year, with virtually all of it going into waste management to improve and protect water, air, and land from contamination. This amounts to about 2.5% of the US total household product, up from 0.9% in 1972. Public support for waste management spending is high. In the year 2000, 64% of Americans expressed "extreme concern" about soil, water, and hazardous waste pollution. Most Americans are unwilling to compromise environmental security to increase job creation and regional GDP. In 1984, 61% of Americans said that environmental conservation was more important than economic development. The percentage was 67% in April 2000.

While the advantages of clean, renewable energy and fuels are obvious, renewable energy resources have only replaced fossil fuels at a very slow pace in the United States over the last 30 years. Despite significant investments in developing and scaling up renewable energy technologies, an integrated, large-scale renewable energy industry has yet to emerge in recent times. The fuel ethanol industry in the United States is the nearest referent to this type of industry. While corn feedstocks account for the majority of US fuel ethanol capability, total production only meets a small portion of national motor fuel demand [68]. Marketable renewable energy resources have not been broadly presented for a variety of reasons: The economics of stand-alone processing systems and plants have historically been unfavorable, funding for novel processing systems and plants has been difficult to secure, transportation and supply facilities are lacking, and long-term competition from fossil energy. However, with the passing of time, an unforeseen corporate environment has emerged, which could propel the renewable energy industry forward. Regrettably, the US energy economy's uncertainty has continued to obscure the events that contributed to this situation.

To boost the use of renewable energy, the US government also passed the Energy Policy Acts in 2005 and the Federal Energy Independence and Security Act in 2007. The United States promotes renewable energy consumption (REC) use (REC) to minimize reliance on oil, mitigate the harmful impact of energy price shocks, and fight global warming. The country makes extensive use of biomass and hydropower. In 2018, the REC in the United States included hydropower (23%), wind (22%), wood (21%), biofuels (20%), solar (8%), waste (4%), and geothermal (4%). The intake of biomass accounts for 45% of total REC. In the last decade, the US REC has risen by 112%. The proportion of renewable energy in the overall energy mix is expanded to 27% [69]. Figure 5.27 depicts the evolution of REC outlets in the United States over the last 10 years. The use of hydropower resources has remained constant. There is also a limit to the rise in geothermal and waste use. However, consumption of solar (1072%) and wind energy (244%) expanded dramatically following the 2008 financial crisis. Subsequent to these energy sources, wood and biofuels have seen fairly modest rises.

Meanwhile, Malaysia has been committed to renewable energy production since 2001 to diversify energy supplies for electricity generation while adhering to the market force theory. However, previous attempts had failed, and the government

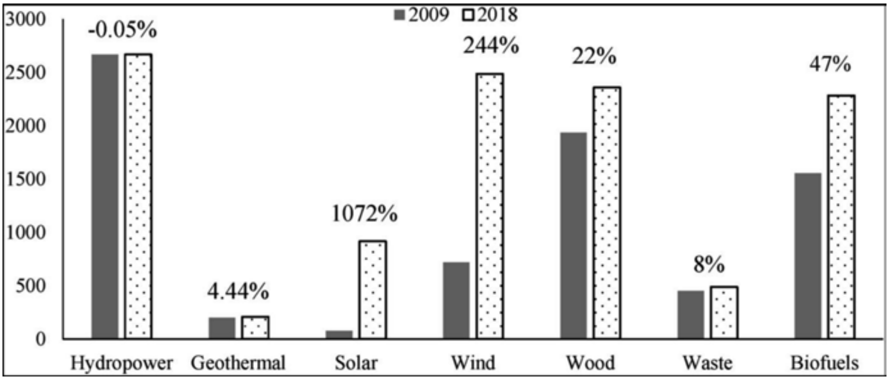


Fig. 5.27 Disaggregated Renewable Energy Consumption from 2009 to 2018 [69]. (Reuse by permission from Elsevier and Copyright Clearance Center)

concluded that the business-as-usual strategy is incompetent and ineffective for long-term growth. Considering the important lessons learned from the previous strategy, the Malaysian government developed a successful policy known as the National Renewable Energy Policy and Action Plan in 2008 to confirm a comprehensive approach for Malaysia's renewable energy industries. The policy seeks to increase the use of renewable energy in the national electricity supply mix while also promoting long-term socioeconomic growth. The policy also emphasizes the importance of a comprehensive research and development (R&D) program and human capital development to accelerate the growth of the renewable energy industry, thus stimulating economic benefits through the development of innovative goods and services [70].

The introduction of a structural R&D program is critical because it will contribute to the local production of pioneering commodities and services, which will help Malaysia's renewable energy industry expand more quickly. Furthermore, by making clean energy technologies cheaper and simpler to use, the local innovation process would aid in its diffusion. As a result, the competitiveness of local companies will be strengthened. The percentage of growth in the use of renewable energy technology, the steady decrease in fossil fuel usage for electricity generation, and the reduction of CO_2 emissions are all observable outcomes of Malaysia's R&D program's significance.

The Renewable Energy Act of 2011 was passed to put in place the Feed-in Tariff (FiT) scheme for increasing renewable energy power generation in Malaysia. Biogas, biomass, mini hydro, and solar photovoltaic (PV) are the four renewable energy options eligible for the FiT. Renewable energy manufacturers may be landholders, company owners, private investors, or even farmers under the FiT mechanism. With their generated device or technology, this process can be reimbursed for renewable energy. The Renewable Energy Fund (RE Fund) guarantees payments to renewable energy suppliers, also known as Feed-in Approval Holders, for a period of 21 years for solar PV and small hydropower, and 16 years for biogas and biomass.

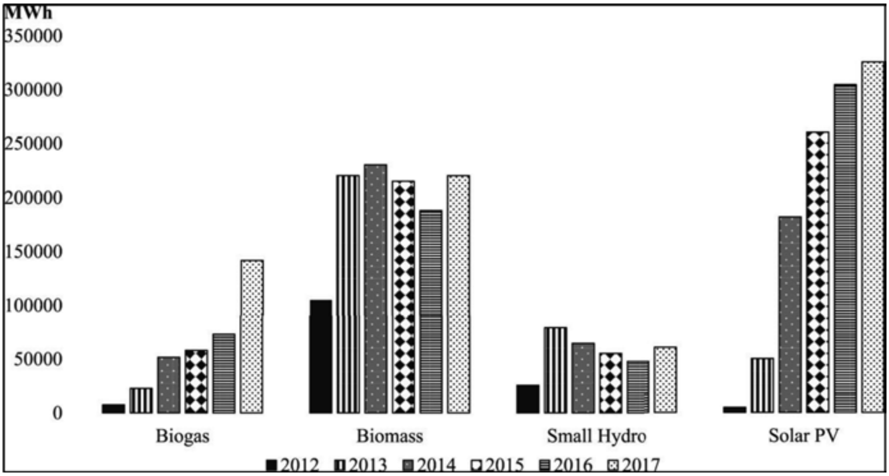


Fig. 5.28 Power generation of commissioned renewable energy installations in Malaysia [70]. (Reuse by permission from Elsevier and Copyright Clearance Center)

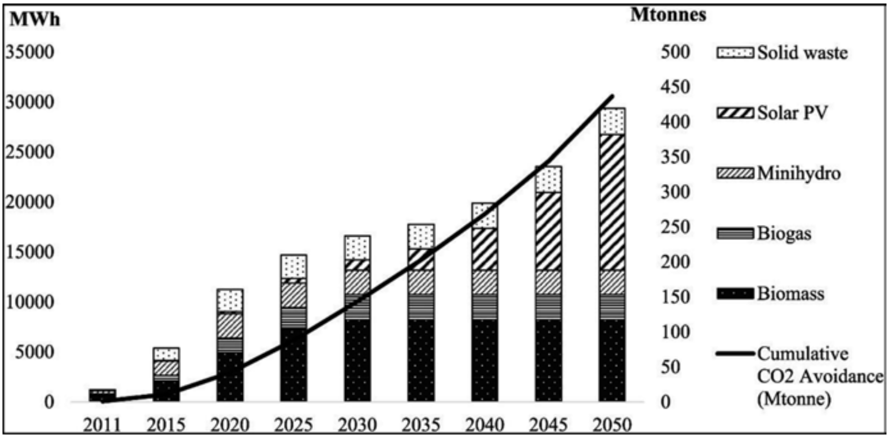


Fig. 5.29 Malaysia's target of renewable energy and CO_2 prevention [70]. (Reuse by permission from Elsevier and Copyright Clearance Center)

The government's efforts were bolstered in the current Eleventh Malaysia Strategy, which included plans to increase renewable energy staff capability and introduce net energy metering (NEM). In 2015, the government made a huge effort to achieve 1% of electricity produced from renewable energy in the energy mix, as shown in Fig. 5.28. Through these measures, renewable energy installed capacity rises by more than 20%, including off-grid construction and cogeneration. Given the massive support earned by the Malaysian government, renewable energy would play an important role in the energy mix and address environmental challenges in the future (Fig. 5.29).

According to a study by M. Chachuli et al. [70], one of the driving forces behind Malaysia's renewable energy generation is the implementation of the FiT scheme. This form of implementation has had a gradual impact on Malaysia's R&D activity in the field of renewable energy resources. A systemic R&D program and a group of professionals will help drive the development of renewable energy industries by developing innovative products and services. Both initiatives will help spread clean energy technology by making it more efficient and affordable. This change will influence renewable energy industry players and will help the country economically. Renewable energy industries in Malaysia can be evaluated holistically for their practicality and economic viability. Furthermore, the government must concentrate on R&D endeavors to ensure the environment's long-term viability and to help the country's socioeconomic growth.

5.7 Summary

Waste generation is estimated to expand rapidly in the coming years in developed and emerging countries. Energy-generating incineration can be a key element of sustainable waste management to ensure the safe disposal of this waste [71]. The fascinating way to reclaim energy from waste is to generate either electricity or CHP, using the conventional but recognized MSW incineration. It is important for any current landfill because of the environmental advantages of the extraction of biogas. Further research would be needed to explore additional technologies that could be of interest to WtE projects, such as plasma arc gasification and thermal depolymerization. If properly managed, solid waste can be a source of employment, jobs, and profits. To reduce the amount of non-degradable materials that include waste paper, metal, glass, plastic bottles, and used tires, the private sector and investors are encouraged to develop solid waste recycling systems.

As far as policy implications go, the government should put in place policies that will promote renewable energy consumption (REC) in the long run. The government will contribute to energy protection and sustainability in this manner. Since REC involves unit root, it has the potential to have a spillover impact on jobs, economic development, capital stock, and other significant macroeconomic variables. Energy incentives and recycling policies, on the other hand, have had a little long-term effect on hydropower and biofuels energy consumption in the world. Past patterns in hydropower and biofuels can be used to predict future movements. A negative shock in hydropower and biofuels energy demand has only a short-term effect. As a result, the government should refrain from intervening in these forms of energy use unless it is appropriate.

Like Malaysia, which has a controlled electricity market, the Feed-in Tariff (FiT) program's funding sources are constrained to a fixed percentage levied on electricity bill owners. The ceiling scheme is essential to ensure that sufficient funds are available to pay renewable energy generators their FiT payments. When Malaysia's electricity market is liberalized, or when a new system with a better solution is implemented in the future, the cap may be removed. Based on current R&D activities carried out in Malaysia, the installed facility of renewable energy resources, especially solar PV, biomass, biogas, and mini hydro, should be expanded. However, due to several constraints, including a lack of power and low wind speed in Malaysia, the result is not applicable to wind energy. Due to limited resources, producing many outputs from any renewable energy source is usually difficult. To speed up the deployment of renewable energy in Malaysia, additional incentive programs must be created. Overall, more effort is needed to achieve superior efficacy in R&D activities in Malaysia's renewable energy production.

The study reveals an increasing global trend toward renewable energy output, with a focus on WtE technologies. The bio-methanation technology, with its relatively higher efficiency and lower capital and operating costs, is found to be the most cost-effective of all the WtE technologies considered. Because of its higher process efficiency and lower environmental emissions, RDF has a high potential for growth and is preferred over incineration. RDF, on the other hand, has drawbacks in terms of initial capital and operating costs, as well as labor capability requirements. The demand for power generation from these WtE technologies is enormous, and if firmly established, it will not only lead to power generation from renewable sources but also reduce landfill costs and related environmental issues.

Glossary

Blackwater Water used to flush toilets, along with the human waste it flushes away.

Calorific Value The calorific value of a substance is known as the number of calories produced when a unit amount of substance is fully oxidized. This value is measured using a bomb calorimeter. The calorific value of coal is calculated using the gross calorific value (HG), which includes latent heat of water vaporization.

Fossil Fuel Coal, petroleum, natural gas, oil shale, bitumen, tar sands, and heavy oils are all examples of fossil fuels. All are carbon-based and were created because of geologic processes operating on the remains of photosynthesis-produced organic matter.

Greywater Wastewaters from drains, tubs, showers, dishwashers, and clothes washers.

MSW Municipal solid waste (MSW) is classified as waste collected by the municipality or disposed of at a municipal waste disposal site. It includes residential, agricultural, institutional, commercial, and municipal waste, as well as waste from construction and demolition.

RDF Refuse-Derived Fuel (RDF) is made from domestic and commercial waste, which contains both biodegradable and non-biodegradable materials. Non-combustible materials such as glass and metals are removed, and the resulting residue is shredded. At waste-to-energy recycling plants, refuse-derived fuel is used to produce electricity.

SRF Solid Recovered Fuel (SRF) is a high-quality alternative to fossil fuels made primarily from commercial waste such as paper, card, wood, textiles, and plastic. Solid recovered fuel has been further processed to increase its consistency and value. It has a higher calorific value than RDF and is used in cement kilns and other similar facilities.

Waste-to-Energy Waste-to-energy (WtE) or energy-from-waste (EfW) is a term that refers to the method of producing energy in the form of electricity and/or heat from waste that has been sorted or processed into a fuel source. WtE is a method of reclaiming resources.

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Chapter 6
Composting by Black Soldier Fly

Hamidi Abdul Aziz, Wen Si Lee, Hadura Abu Hasan, Hasnuri Mat Hassan, Lawrence K. Wang, Mu-Hao Sung Wang, and Yung-Tse Hung

Abstract Solid waste generation around the world is rising and expected to achieve 3.40 billion tons by 2050. The waste generated must have proper waste management to reduce the effect on human health and environmental pollution. Developing countries with large populations such as India and China have produced a large amount of solid waste. Organic waste has the highest proportion in solid waste generation, which consists of food waste and animal manure. There are various methods that can be carried out to manage solid waste; one of the methods is composting where the black soldier fly (*Hermetia illucens*) can be used as a composting agent to decompose the organic waste into biomass without generating any odor and pollution to the surrounding environment. The current organic waste management and

H. A. Aziz (✉)
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Solid Waste Management Cluster, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: cehamidi@usm.my

W. S. Lee
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: leewensi@student.usm.my

H. A. Hasan · H. M. Hassan
School of Biological Sciences, Universiti Sains Malaysia, Minden, Pulau Pinang, Malaysia
e-mail: hadura@usm.my; hasnurimh@usm.my

L. K. Wang · M.-H. S. Wang
Lenox Institute of Water Technology, Latham, NY, USA

Y.-T. Hung
Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, OH, USA
e-mail: y.hung@csuohio.edu

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practice adopted for composting organic waste are reviewed. The design and performance of the black soldier fly are also reviewed in this chapter. A landfill is not recommended to manage the waste due to the need of large land use and leachate production. Incineration is also not suitable to manage the waste due to the high emission of toxic gases although it can reduce the waste effectively. However, both the methods are still adopted in many countries especially developing countries due to easy to operate and low cost. Composting is limited to organic waste, and fewer countries utilize this method for waste management. There are various types of composting to manage organic waste and co-composting methods to enhance the degradation of organic waste. Black soldier fly has the potential to decompose the organic waste into biomass through composting. However, rearing the black soldier fly is challenging because the growth of the black soldier fly is affected by various factors such as pH, relative humidity, light intensity, temperature, moisture content, and nutrient of the substrates. Nutrients such as protein and fat are essential for black soldier fly for growth. The substrates can undergo mixing or fermentation to enhance the nutrients to allow the black soldier fly has better growth performance. The compost materials can be used as fertilizer and soil amendment to improve the yield of the plants. The black soldier fly larvae can act as animal feed where the animal consumes the nutrients from the larvae for growth. The biodiesel can be produced by extracting the lipids from the larvae. Many countries had conducted various studies on the black soldier fly technology; however, still there are some challenges when conducting the study, especially the greenhouse gas emissions, and iterative researches must be carried out to identify the gaps and enhance the knowledge on the technology.

Keywords Black soldier fly · *Hermetia illucens* · Composting · Organic waste · Waste management · Biodiesel · Animal feed · Frass fertilizer · Global warming potential · Co-composting

Acronyms

$CD8^+$ T	Cytotoxic T cells
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DBU	1,8-Diazabicyclo[5.4.0]undec-7-ene
DHA	Docosahexaenoic acid
H_2O	Water
H_2O_2	Hydrogen peroxide
H_2S	Hydrogen sulfide
HNO_3	Nitric acid
NH_4^+	Ammonium ion

NO_3^-	Nitrate ion
O_2	Oxygen
SO_4^{-2}	Sulfate ion
SO_2	Sulfur dioxide

Nomenclature

CO_2eq	Carbon dioxide equivalent
cm	Centimeter
°C	Degree Celsius
°F	Degree Fahrenheit
g	Gram
h	Hour
kg	Kilogram
L:D	Light: dark
m	Meter
mg	Milligram
mL	Milliliter
min	Minute
mol	Mole
μ	Mu
%	Percent
lb	Pound
s	Second
t	Tons
°S	South
°N	North

6.1 Introduction

In these few years, the waste generation keeps raising, and the global waste generation expects will achieve 3.40 billion tons in 2050. The waste generation is anticipated to increase with the economic development and growth of the population, and the regions with high proportions of growing low-income and lower-middle-income countries are expected to face a major increase in waste production [1]. The region that produces the highest municipal solid waste is East Asia and the Pacific Region. China has the greatest share of global municipal solid waste, which is more than 15% due to large population in the country. Several types of waste such as food waste, plastic waste, glass, metal, wood, paper, and others are generated by human. Waste composition is the distribution of types of materials in municipal solid waste.

Food waste is the most common waste that generates almost 50% of the global municipal solid waste; every year millions of tons of food are wasted, especially fruit and vegetables, resulting in environmental pollution [2].

Several types of waste treatment can be utilized to manage the waste such as incineration, landfill, anaerobic digestion, and composting [3]. Incineration is the thermal treatment that has the benefit to reduce the volume of waste and making it harmless, by the demolition of pathogens and toxic chemicals, where the solid waste is demolished thoroughly through the high temperature [4]. Landfill is the most common waste management that has been applied in many countries; however, recently most of the countries have tried to minimize reliance on the landfill due to its need for large land use [5]. Composting is a controlled microbial decomposition of organic solid waste under aerobic condition, where the microorganisms transform the waste into a chemical humus-like stable product [4]. There are various types of composting methods such as turned windrows, aerated static piles, vermicomposting, and in-vessel composting [5]. The quality of compost products can be enhanced by mixing different substrates, and the products can be used as fertilizer in the agriculture field. Organic solid waste management is a vital challenge throughout the world, and a lack of knowledge on the management will result in environmental deterioration and human health hazards [4].

Black soldier flies are small and harmless insects that have the ability to convert organic waste into useful compost products through composting. Black soldier fly larvae or *Hermetia illucens* is a species that could break down organic waste efficiently, especially the green matter with high nitrogen content in decomposing plant materials. The black soldier fly larvae are more preferred to stay in warm and moist conditions [6]. There are five stages in the black soldier fly life cycle, which are egg, larva, prepupa, pupa, and adult [7]. Various factors affect the growth of black soldier fly larvae such as temperature, light intensity, relative humidity, pH, and type of substrates. Those factors should be in optimum condition so that the black soldier fly can grow well [8]. The black soldier fly larvae can be fed with food waste, grains, and manure, which consist of sufficient nutrients for black soldier fly larvae to grow [9]. The larvae are pale beige with darker rings around the body segments, but they turn dark grayish brown when mature. The larvae can consume twice their body weight daily and convert the organic waste into little fat bodies containing up to 43% protein and 35% fat [6]. However, some of the substrates are not suitable for feeding and may affect the survival of larvae, especially sewage sludge [10]. The nutrients of substrates can improve by mixing with other substrates or undergoes microbial fermentation; thus the black soldier fly larvae can have better growth performance and gain sufficient nutrients from the substrates [11].

Black soldier fly technology can be utilized in our daily life such as used as alternative protein, animal feed, and waste management. The black soldier fly contains high-quality protein which is up to 50% can be used as a source of animal protein for humans and animals [9]. Waste treatment using black soldier fly larvae can reduce the organic waste through the decomposition process, the final products decomposed by black soldier fly larvae can be used as larvae protein and compost [12]. Since black soldier fly larvae contain high protein and fat content, they can be used as animal feed to replace soybean meal and fishmeal. The fat in black soldier fly larvae can be converted into biodiesel; the quality of biodiesel is based on the fatty acid profile that lipids of black soldier fly larvae fed on different substrates. The waste residue after the decomposition by the black soldier fly larvae can be used as fertilizer in agriculture fields to enhance the growth and yield of the plant [13]. The black soldier fly technology has been applied in many countries such as China, South Korea, Malaysia, and other countries due to its eco-friendly and beneficial to humans and animals. However, some challenges and limitations using the black soldier fly technology must be taken into consideration especially the global warming potential and greenhouse gas emissions, thus the black soldier fly technology can be used safely and efficiently.

Since food waste has the highest waste generation rate, the composting method can be considered in waste treatment management. Composting is chosen as waste treatment management to remove the food waste because this method can reduce waste safely and effectively. With the help of organisms, composting will not bring much bad influence to the environment and human health. This method not only reduces the emission of toxic gases but also enhances the yield of plantation and soil conditions. There are various studies conducted using the composting method to decompose those food waste. Black soldier fly larvae are one of the organisms used in composting to remove the organic waste and convert the organic waste into compost and used as fertilizer and soil conditioners. The present chapter aims to focus on the current management of organic waste and the current practice of the composting system. Moreover, this study highlights the characteristic of black soldier fly larvae and the importance of black soldier fly larvae for sustainable organic waste management to generate high-quality biomass. The black soldier fly technology is utilized in various countries, and the challenges of using black soldier fly technology are discussed in detail.

6.2 Current Management on the Organic Wastes

6.2.1 Sources of Organic Waste

6.2.1.1 Food Waste

Food waste is defined as any food or inedible components of food that has been removed from the food supply chain and maybe retrieved or discarded [14]. Due to poor weather, processing issues, overproduction, and an uncertain market, an estimated 125–160 billion pounds of food waste is generated every year [15]. Food waste is the most common waste that generates almost 50% of the global municipal solid waste; every year, millions of tons of food are wasted, especially fruit and vegetables, resulting in environmental pollution [2]. However, the global share of organic waste will decrease from 47 to 39%, while all other waste compositions will increase, especially paper waste [16]. Figure 6.1 shows the waste generation in the

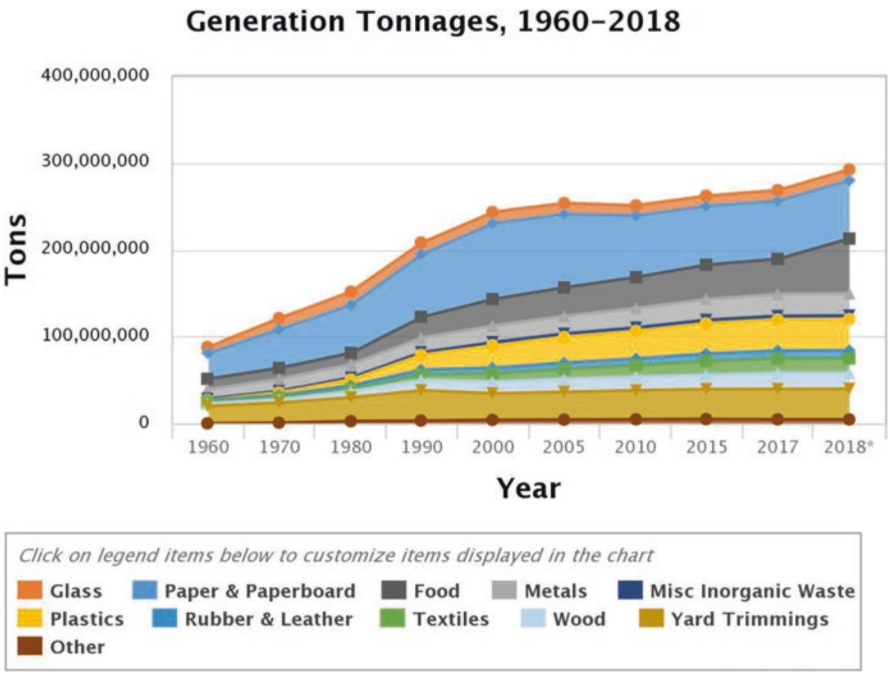

Fig. 6.1 The United States waste generation based on waste types from 1960 to 2018 [17]

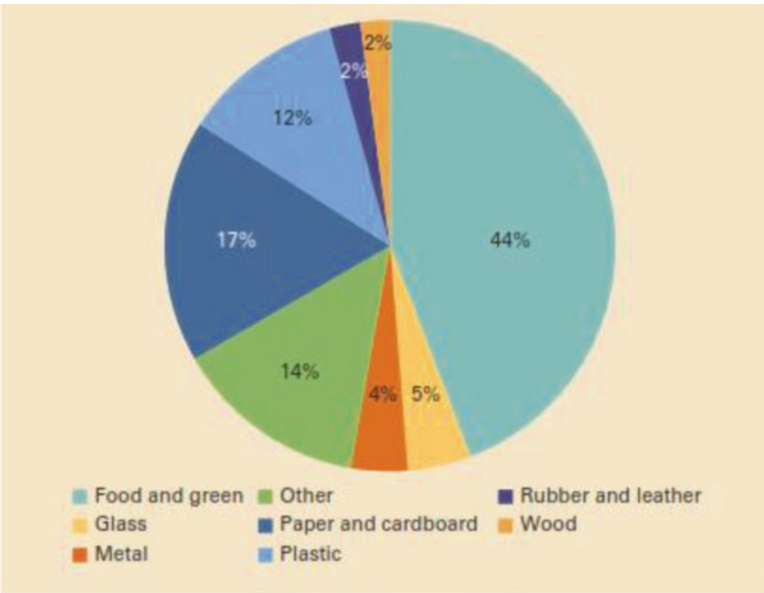

Fig. 6.2 Global waste composition in percentage [1]

United States based on waste types from 1960 to 2018. Food waste is the fourth largest waste material category in the United States; approximately 63.1 million tons of food waste had been generated in 2018 [17].

Food waste is generated by farms, households, industrials, restaurants, and institutions [15]. When compared to other wastes, food waste has the greatest proportion of waste composition as shown in Fig. 6.2. In high-income countries, less food waste is generated; low-income countries will generate greater food waste due to increased economic development and population expansion as shown in Fig. 6.3 [1]. Every year, China and India have generated high household food waste compared to other countries at approximately 92 million and 69 million metric tons, respectively, due to large population [2].

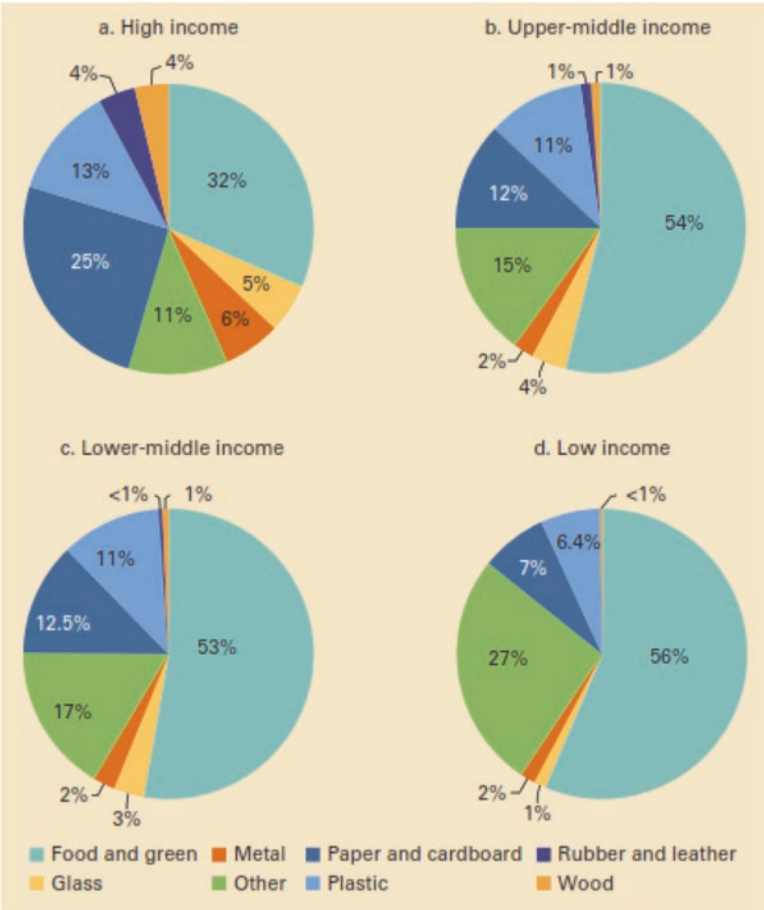

Fig. 6.3 Waste composition based on the income level [1]

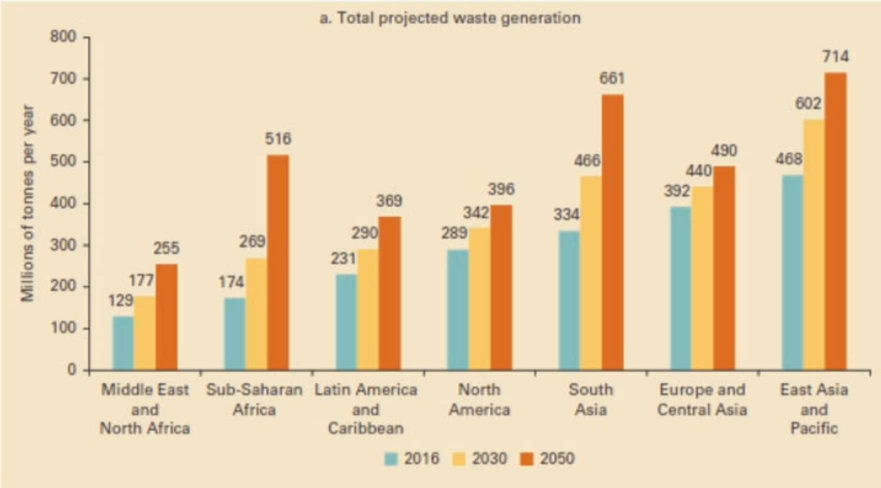

Fig. 6.4 Total projected waste generation based on region [1]

Table 6.1 Beneficial uses of manure [22]

Manure component	Beneficial uses	Advantages
Nutrients	Compost, fertilizer, biomass conversion	Cost savings on fertilizer and income generation from sales of manure
Organic matter	Soil amendments/structuring	Improves soil structure and water holding capacity; impacts on crop yield
Solids	Bedding	Savings on the cost of bedding materials
Energy	Biogas, bio-oil, and syngas	Supplementary energy for farm use; reduced reliance on fossil fuels; income generation from sales of energy
Fiber	Peat substitute, paper, and building materials	Potential environmental liability turned into useful commodities

Kaza et al. [1] stated that waste generation will increase in the future, for example, in East Asia and the Pacific region, waste generation increases from 468 million tons per year to 714 million tons per year between the year 2016 and year 2050 as shown in Fig. 6.4. When an excess of food waste is generated, it may cause the loss of biodiversity, high land use, increased carbon footprint, and accelerate climate change [18]. Tiseo [2] revealed that the waste generation of food waste not only costs the global economy hundreds of billions of dollars every year and uses up the resources but also damages the environment and promotes climate change. Methane is generated from the food waste when undergoing landfill activities and is released into the atmosphere, and this greenhouse gas may cause global warming. Kim et al. [19] found that the most economical way to reduce food waste is to use black soldier fly larvae, which rapidly decompose and less odor is produced.

6.2.1.2 Animal Manure

Animal manure is another type of organic wastes that can be composted by the black soldier fly larvae. Animal manure, which is generated on agricultural farms, is one kind of soil amendment that may assist restore nutrients to the soil and improve the growing conditions for the next crop. Animal manure is organic matter that has been composted to eliminate pathogens and break down more quickly for plant uptake. Various types of animal manure are used in composting such as chicken, cow, sheep, and goat. However, human manure is not suitable to use because it may contain drugs and diseases [20]. The manure that is composted would generate different components, which help to improve the soil condition and can be used as fertilizer. The type of components are nutrients, organic matters, energy, and fibers [21].

Animal manure consists of various useful components that can be applied in our daily life (Table 6.1). Each manure has its characteristics generated from the typical animal production operations which are shown in Table 6.2. Nutrients in animal manure such as nitrogen, potassium, and phosphorus are important for land application and must achieve the nutrient requirements of the crop being grown [22]. On the other hand, livestock manure contains toxic heavy metals and pathogenic microorganisms that may cause environmental pollution, thus proper treatment is required before it is applied to agricultural land. If treated or used improperly, the manure may pollute the rivers, soil ecosystems, and underground (Table 6.3) [23]. Various types of pathogens stay in the manure such as bacteria, viruses, protozoan, and helminthic parasites [24]. To control the content of heavy metals and pathogens from spreading to the environment, proper treatment methods need to be considered, thus it can prevent environmental pollution and affecting human health.

The heavy metals in the manure can be removed through the sorption process; modified biochar could improve the sorption efficiency of heavy metals. The biochars derived from the pig manure at different pyrolyzing temperatures were oxidized and thiolated using hydrogen peroxide and 3-mercaptopropyltrimethoxysilane, respectively [25]. Wang et al. [25] indicated that the oxidation and thiolation reduced the aromaticity and ash content and increased the polarity and specific surface area and pore volume of biochars. The heavy metal sorption by biochars happens via cation exchange, precipitation, cation-π EDA interactions, and complexation. Therefore, the oxidization and thiolation treatments of animal manure biochars could enhance the reduction of heavy metals that pollute the environment. Antibiotic resistance genes are new environmental pollutants that may affect global public health. When animal manure is utilized in the agriculture field, it may increase the antibiotic resistance genes in the soil [26]. Huang et al. [26] revealed that there was a significantly increased antibiotic resistance genes abundance in the soil-lettuce system when poultry and swine application were applied due to the shared bacterial distribution.

Good manure management needs to be practiced to protect the environment. The animal waste management system can be defined as a planned system with relevant components installed and managed to control and use by-products of animal

Table 6.2 Characteristics of manure of farm animals (per 1000 lb animal unit per day) [22]

Animal category	Weight (lb)	Moisture (%)	Total solid (lb)	Volatile solid (lb)	Biological oxygen demand (lb)	Nitrogen (lb)	Phosphorus (lb)	Potassium (lb)
Dairy manure								
Lactating cow	97–130	87	12–17	9.2–13	2.1	0.66	0.11–0.15	0.30–0.38
Calf	83	83	9.2	7.7	–	0.42	0.05	0.11
Dry cow	51	87	6.6	5.6	0.84	0.30	0.042	0.10
Beef manure								
Beef cow in confinement	104	88	13	11	2.5	0.35	0.08	0.25
Growing calf in confinement	77	88	9.2	7.7	1.7	0.45	0.08	0.29
Finishing cattle	65	92	5.2	4.3	1.0	0.36–0.50	0.044–0.076	0.25
Swine manure								
Gestating sow	25	90	2.5	2.3	0.84	0.16	0.05	0.11
Lactating sow	59	90	5.9	5.4	2.0	0.45	0.13	0.28
Boar	19	90	1.9	1.7	0.66	0.14	0.05	0.09
Poultry manure								
Layers	57	75	15	11	3.3	1.1	0.33	0.39
Broiler	88	74	22	17	5.3	0.96	0.28	0.54
Turkey toms	34	74	8.8	7.1	2.3	0.53	0.16	0.25
Turkey hen	48	74	12	9.8	3.0	0.72	0.20	0.31
Duck	102	74	27	16	4.5	1.0	0.35	0.50

Table 6.3 Environmental risk of livestock manure [23]

Contaminants	Explanation
Heavy metals	Heavy metal accumulation in plants may cause a health risk when humans or animals consume. The accumulation of heavy metals in the manure not only influences the soil fertility and product quality but also develops the migration of metal through leaching and runoff
Pathogenic microorganisms	Bacteria and viruses will increase the ability for spreading disease through water runoff or other routes; this may affect the human and animal health

Table 6.4 Effect of good and poor manure management [27]

Good manure management	Poor manure management
Reduced cost of commercial fertilizers	Loss of fertilizer nutrients
Improved production efficiency	Odor and animal health problems
Improved animal health	Negative social and regulatory climate for agriculture
Protection of water resources and air quality	

Table 6.5 Sustainable element benefits of manure management [22]

Sustainable elements	Advantages of manure management
Environment	Prevents the environmental impacts on air, water, soil, wildlife, and marine
	Protects human health in communities and at waste management facilities
	Minimizes the risk associated with the waste
	Improves occupational health
	Reduces greenhouse gas emissions from waste
	Reduces litter and odor
Economy	Increase business opportunities
	Provides savings to businesses
	Achieves economic savings by improvements in human health and the environment, leading to higher productivity
Social	Creates employment
	Integrates and professionalized employment in the informal section
	Encourages changes in community attitudes and behaviors

production that helps and improves the quality of water, soil, air, plant, and animal resources [22]. Table 6.4 shows the good and poor manure management. If improper manure management may affect the quality products of manure and human health. Table 6.5 shows the characteristics of manure of farm animals (per 1000 lb animal unit per day) [22]. Those manures that undergo manure management can bring advantages based on the three sustainable elements such as social, environment, and economy (Table 6.6). Various manure treatment methods to treat the manure such as

Table 6.6 Waste types and applicable treatment methods (NA: impossible composition-treatment combinations) [16]

	Waste management				
Waste types	Landfill	Incineration	Recycling	Composting	Dumps
Organic waste			NA		
Paper					
Plastic				NA	
Metal		NA		NA	
Glass		NA		NA	
Other				NA	

composting, anaerobic digestion, and manure solid–liquid separation method [28]. In future manure management, the management must ensure a safe environment, availability of low-cost and effective manure management methods is used [22].

6.2.2 Organic Waste Management

Due to the increase in population, the waste generation rate is getting higher. Decomposition of these organic wastes may result in large-scale pollution of land, water, and air, thus safe and cost-effective waste disposal is a significant issue [4]. Therefore, suitable waste management needs to be considered to ensure it will not affect the environment and human health. There are a few types of waste treatment technologies that could help to reduce the waste and convert the waste into fertilizer or energy, such as anaerobic digestion, composting, landfill, and incineration [14]. Table 6.6 shows the waste types with their applicable treatment methods. Reduction of usage of source or reuse is the most preferred waste management, whereas disposal or incineration is not recommended for waste management because it may cause environmental pollution. Figure 6.5 shows the waste management hierarchy.

Different countries will have different waste management based on waste generation and waste composition (Fig. 6.6). The usage of dumps decreases as the countries are getting richer, and landfill activities are the most essential waste management for most countries due to low cost and ease of operation [16]. Since the waste generation keeps increasing, thus the number of wastes in the waste management is also increasing from 1960 to 2018 in the United States. Recycling is the most preferred waste management because most of the waste materials can be recycled such as metal, glass, and paper, thus the number of wastes that undergo the recycling treatment getting higher (Fig. 6.7) [17].

The word “landfill” refers to the physical structures used to dispose of solid wastes and solid waste residuals in the earth’s surface soils [29]. Landfills can be divided into three categories such as simple landfill, controlled landfill, and sanitary landfill [30]. The municipal solid waste landfill receives residential waste, non-hazardous waste, industrial waste, and construction and demolition waste. However,

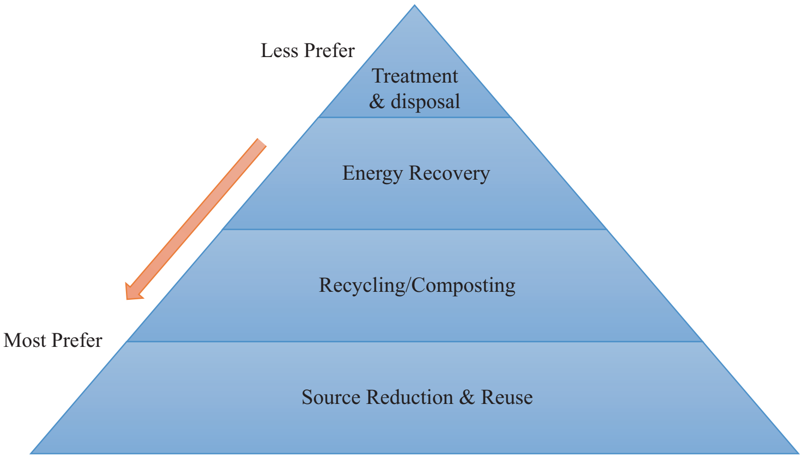

Fig. 6.5 Waste management hierarchy

those wastes that are disposed of in landfills may include pathogenic microorganisms or poisonous chemicals that are hazardous to soil [31]. Therefore, solid waste landfills must be built to preserve the environment from contaminants found in the solid waste stream [4]. Due to high organic waste composition and low level of waste management techniques in the developing countries, high pollution potentials from leachate had been generated [32]. The leachate is a liquid effluent produced through the interaction of rainwater and degradation products of waste (Fig. 6.8).

A sanitary landfill is an engineered facility and is managed to minimize public health and environmental effects while disposing of municipal solid waste [29]. Landfill gas is composed mostly of methane and carbon dioxide produced by the anaerobic decomposition of organic waste in landfill operations [3]. The amounts of emission of methane and carbon dioxide generated from the landfill activities are 14.7 and 221.35 kg/ton, respectively, as shown in Table 6.7 [33]. Landfill leachate is generated by infiltrating rain percolating through the waste and leaching of contaminants [3]. To overcome these problems, more practices are carried out to reduce the gas emission and contaminants infiltrate into the ground. The landfill's land cannot be reused for building construction unless the restoration is conducted to stabilize the ground [5]. The advantages and disadvantages of landfill activities are shown in Table 6.8. In 2018, an estimated 146.1 million tons of municipal solid waste were landfilled, food waste had the highest component at about 24%, followed by plastic waste at about 18% in the United States [17]. In the United States, various wastes can be decomposed through landfill activities, and the materials that are applied in the landfill activities are shown in Fig. 6.9.

Anaerobic digestion is another waste treatment method that can reduce the waste from the environment. The most successful and innovative waste-to-energy technique is anaerobic digestion [4]. Anaerobic digestion is a microbially biochemical

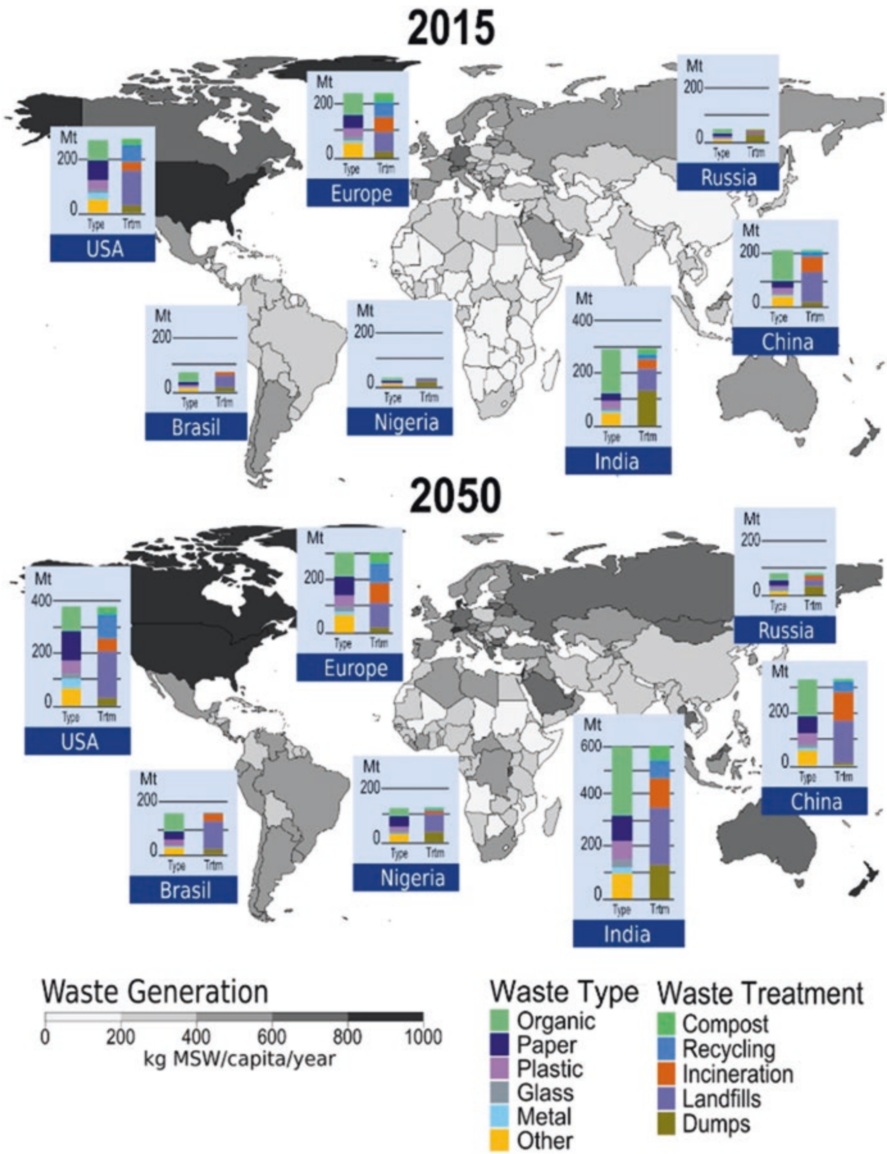

Fig. 6.6 World maps of waste generation, type, and treatment, 2015 and 2050. National per capita generation values (kg) in grayscale shading, whereas bar charts show total production of waste types and treatments presented for regionally representative countries and regions (in the case of the EU). Bar chart values are in terms of the total amount of waste generated (Mt) for the country/region [16]

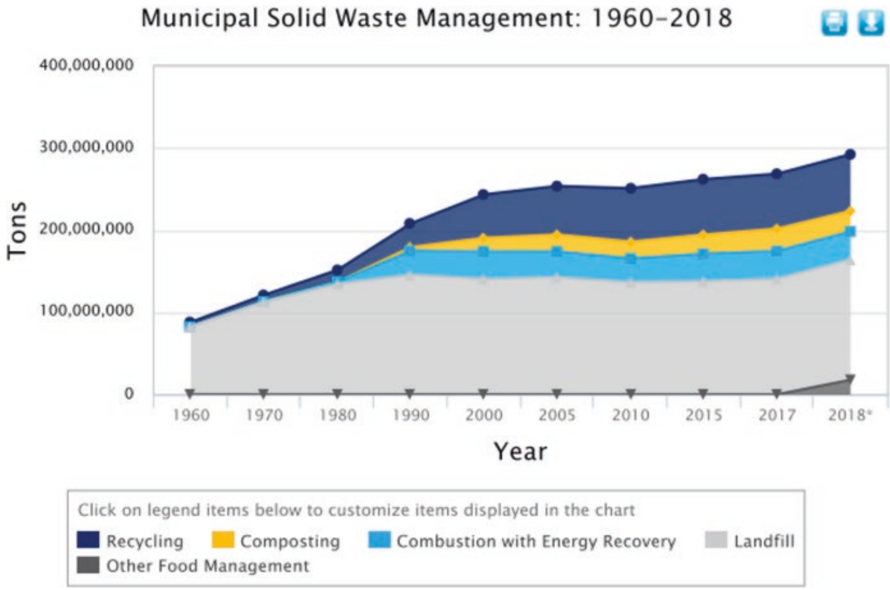

Fig. 6.7 Municipal solid waste management from 1960 to 2018 [17]

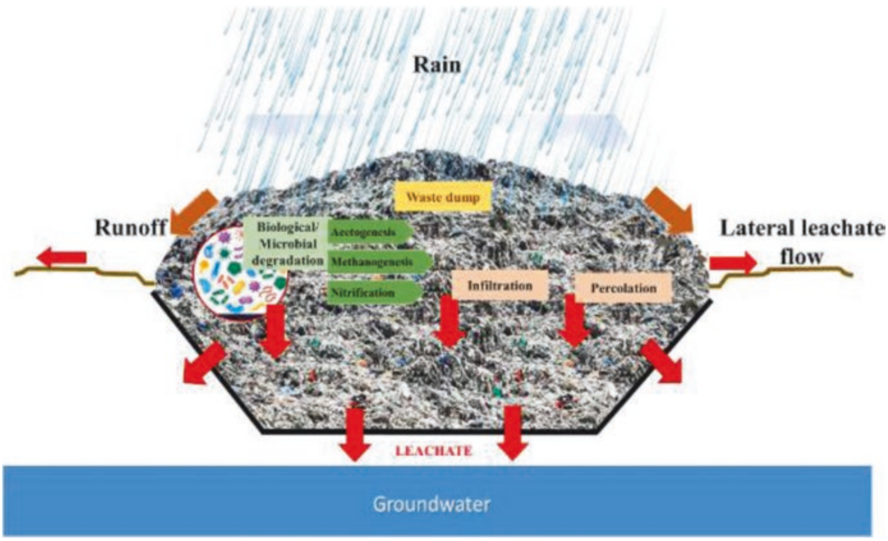

Fig. 6.8 Conceptual model of leachate generation [32]

Table 6.7 Inventory of treatment process of food waste [33]

Emissions	Substances	Anaerobic digestion	Landfill	Incineration	Composting	Heat-moisture reaction
Emissions to air (kg/t)	CO_2	36.54	221.35	676	42.64	48.35
	CO	0.012	0.68	0.059	0.104	0.013
	CH_4	3.05	14.70	3.12	3.06	3.05
	H_2S	5.05E-05	9.84E-04	2.44E-04	3.7E-05	0
	NO_x	0.075	0	0	0.305	0.12
	SO_2	0.23	0.14	0.087	0.087	0.37
	VOC	0.00045	0.0166	0.00245	0	0.0008
	$PM_{2.5}$	0.0014	0.0016	0.00115	0.0146	0
Emissions to water (kg/t)	AOX	5E-07	0.085	0.0038	3.95E-06	6.5E-07
	BOD	0.0028	0.00035	0.0001	0.0377	0.00045
	COD	0.0065	0.018	0.01	0.0475	0.001
	Phosphate	0.003	0.2665	0	0.014	0
	Sulphate	0.065	0.0605	0.037	0.3405	0.001
	Arsenic	5.1E-06	3.85E-06	1.95E-06	4.7E-05	1.15E-06
	Cadmium	1.25E-06	9.5E-07	1.15E-06	2.0E-05	1E-07

VOC volatile organic compound, *$PM_{2.5}$* fine particulate matter, *AOX* adsorbable organically bound halogens, *BOD* biological oxygen demand, *COD* chemical oxygen demand

Table 6.8 Advantages and disadvantages of waste treatment method

Treatment method	Advantages	Disadvantages	Reference
Incineration	High degree of reduction	Require high cost and technology	[30]
	Small land use	Produce dioxins and other harmful gases	
	Used as recycle energy for heating and power generation	Poor stability	
Landfill	Low cost Easy operation	Soil pollution	[34]
		Water contaminants	
		Human health risk	
Composting	Acts as organic fertilizer Acts as soil conditioners	Need for sorting	[30]
		High cost	
		Only can be used for organic waste	
Anaerobic digestion	Reduction of pathogen	High capital cost	[4]
	Reduction of pollution	Monitoring of performance and strict process control is required	
	Generates energy and electricity from biogas	Slow microbial conversion rate	

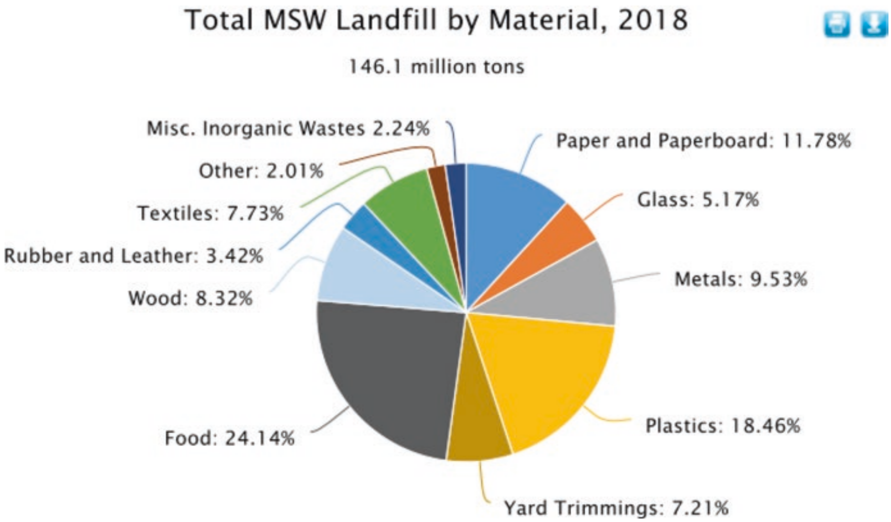

Fig. 6.9 Total municipal solid waste under landfill activities in the United States by materials, 2018 [17]

degradation of complex organic material into simple organics and dissolved nutrients [35]. Anaerobic digestion is the microbial conversion process of organic wastes into methane and carbon dioxide mixture known as biogas, anaerobic biomass, and organic residual in the absence of oxygen [4]. The production of bioenergy from anaerobic digestion is a promising alternative to climate change reduction and is considered a viable treatment technology for waste management [36]. There are various types of anaerobic digestion systems such as single-stage, wet and dry system, two-stage system, and batch system The anaerobic digestion of organics waste can be expressed as below: [37]:

$$[\text{complex organics}] + \text{heat} \rightarrow CO_2 + CH_4 + H_2S + NH_4^+ \tag{6.1}$$

Anaerobic digestion will undergo a few biochemical processes to generate the nutrients and biogas, such as hydrolysis, fermentation, acetogenesis, and methanogenesis [5]. The biogas generated from anaerobic digestion is lower compared to landfill activities, in which the amount emission of methane is 3.05 kg/ton and carbon dioxide is 36.54 kg/ton shown in Table 6.7 [33]. The advantages and disadvantages of anaerobic digestion are shown in Table 6.8. Before 2018, anaerobic digestion is not common waste management utilized by the United States. Started from 2018, this waste management had been applied for municipal solid waste management, especially food waste (Fig. 6.10) [17].

Incineration is the process of controlled and complete combustion of solid waste in an oxidizing atmosphere [4]. This method can generate energy and solid residues as well as flue gas emitted into the atmosphere [3]. Under high-temperature conditions, the wastes undergo a chemical reaction with the oxygen to produce heat and

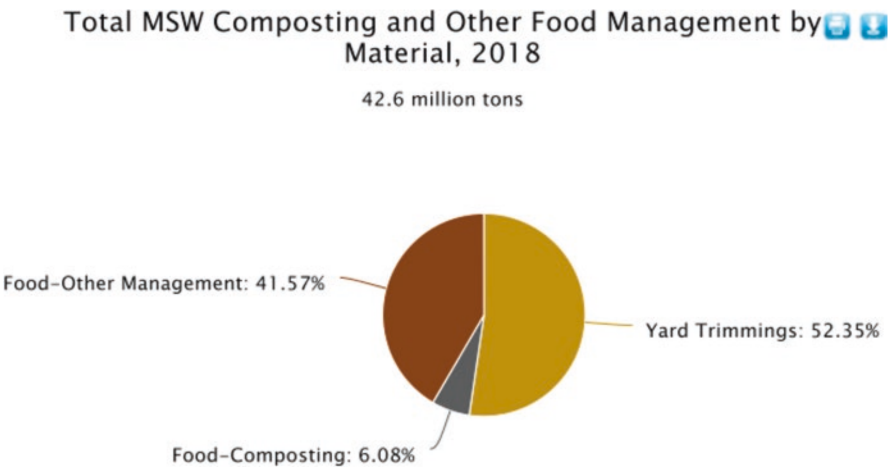

Fig. 6.10 Total municipal solid waste under composting and other food management in the United States by material, 2018 [17]

less stable solid residue; however, it can kill the bacteria and viruses [30]. Ding et al. [38] found that the incineration process is widely used in China started in the year 2009, and the treatment rate is increased significantly until the year 2018 as shown in Fig. 6.11. Although incineration can treat the waste in a short period, it can emit a large amount of carbon dioxide compared to other treatment methods that lead to acid rain and the greenhouse effect [33]. The advantages and disadvantages of incineration are shown in Table 6.8.

Composting can be defined as the aerobic biological decomposition of organic waste under controlled conditions [37]. The purposes of composting used as a waste treatment method are to decompose organic fraction of waste to a stable state, reduce waste volume, weight, and moisture content, minimize potential odor, and increase nutrients for agricultural applications [4]. In the composting method, the emission amount of carbon dioxide is 42.64 kg/ton and methane is 3.06 kg/ton as shown in Table 6.7 [33]. In the United States, only 2.6 million tons of food waste undergo the composting method, which is about 6% of the generation of wasted food in 2018 (Fig. 6.10) [17]. The composting system can be expressed as below: [37]:

$$\begin{aligned}&[\text{complex organics}] + O_2 \rightarrow CO_2 + H_2O + NO_3^{-} + SO_4^{-2}\\&+[\text{other less complex organics}] + [\text{heat}]\end{aligned} \tag{6.2}$$

Compost is the stabilized and sanitized product of composting, which is beneficial to plant growth [3]. It acts as growing media and soil conditioners; however, it cannot be directly used as growing media without any modification [5]. Few types of organisms help in composting those organic wastes such as bacteria, fungi [3], and insects [39]. There are few types of composting technologies that are commonly used to decompose those wastes such as turned windrow, aerated static piles, and

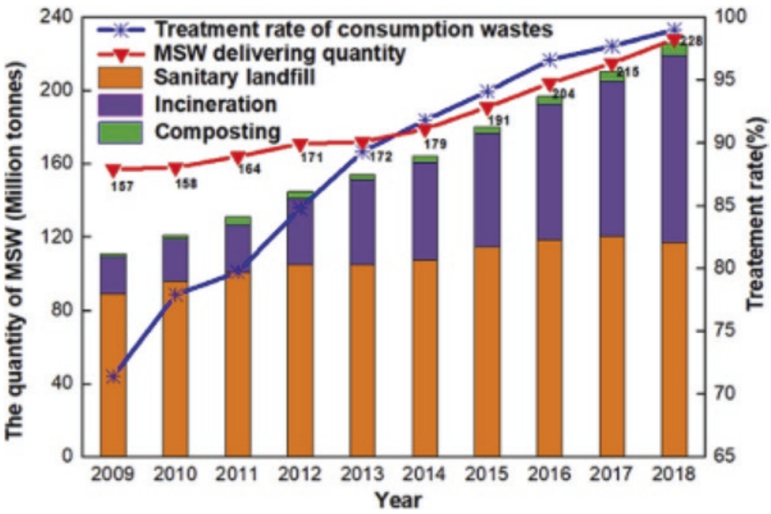

Fig. 6.11 Municipal solid waste generation in China between 2009 and 2018, and the corresponding treatment quantity using landfill, incineration, and composting with the total treatment rate of consumption waste [38]

in-vessel systems [5]. In China, the treatment rate for the composting method is low compared to incineration and landfill activities because this method is only restricted to organic waste (Fig. 6.11) [38]. The advantages and disadvantages of composting are shown in Table 6.8.

6.2.2.1 Waste Management in China

China has the largest population in the world, the waste generated every year is high reported for over 15% of the global municipal solid waste volume. The amount of disposed waste in China had risen three times in three decades since 1990 [40]. The amount of municipal solid waste generated in mainland China cities had increased from 135 million tons in 2001 to 228 million tons in 2018 (Fig. 6.12) [41]. The municipal solid waste composition in China is influenced by economic status, culture, energy consumption, and climate. The municipal solid waste compositions in China are governed by 55.86% of food waste. The choice of technology and waste management treatment is based on the composition of municipal solid waste of a country [42].

The most common waste handling in China is the sanitary landfill, where over half of the trash undergoes this waste treatment method. The volume of waste generated in China had been continuously rising, and the number of sanitary landfill sites had reached approximately 663 in 2018 (Fig. 6.13) [40]. There are some challenges of waste disposal on landfill sites in China such as loss of land for value-added development, shortage of available landfill sites, emission of landfill gases, soil and

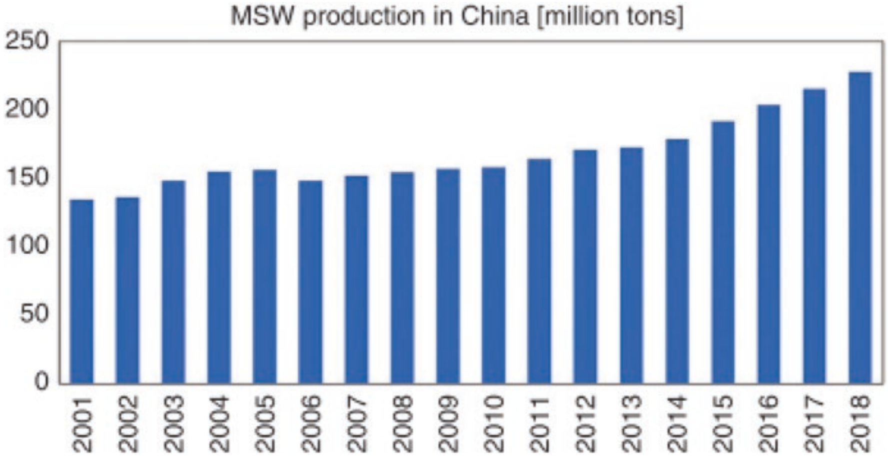

Fig. 6.12 Production of municipal solid waste in China [41]

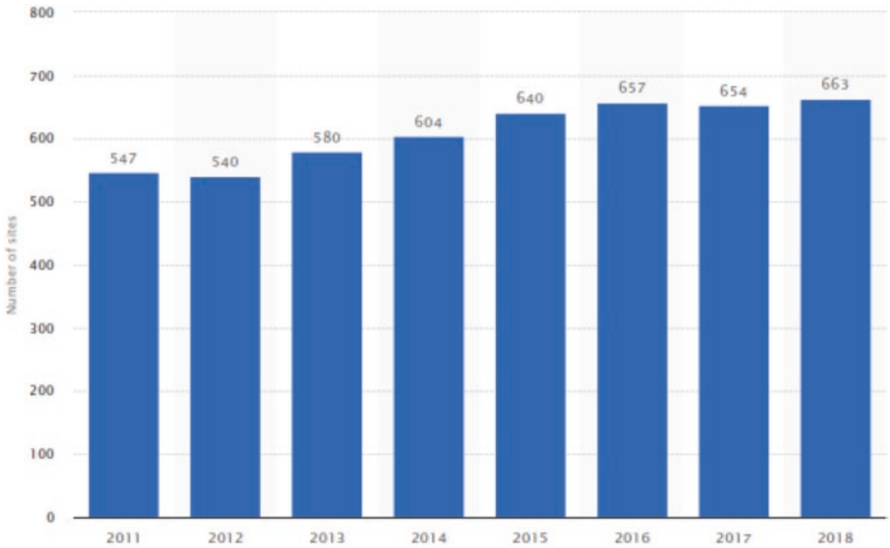

Fig. 6.13 Number of sanitary landfill sites in China from 2011 to 2018 [40]

water contamination, and harm to human health [41]. There is a limitation in choosing a new landfill site in China because rapid urbanization increases the value of the urban land area. The landfill site which is located at a further distance from the main collection point requires high transfer cost as well as additional investment in the infrastructures. Therefore, the selection of proper landfill location and infrastructure is important to enhance municipal solid waste management in China [42].

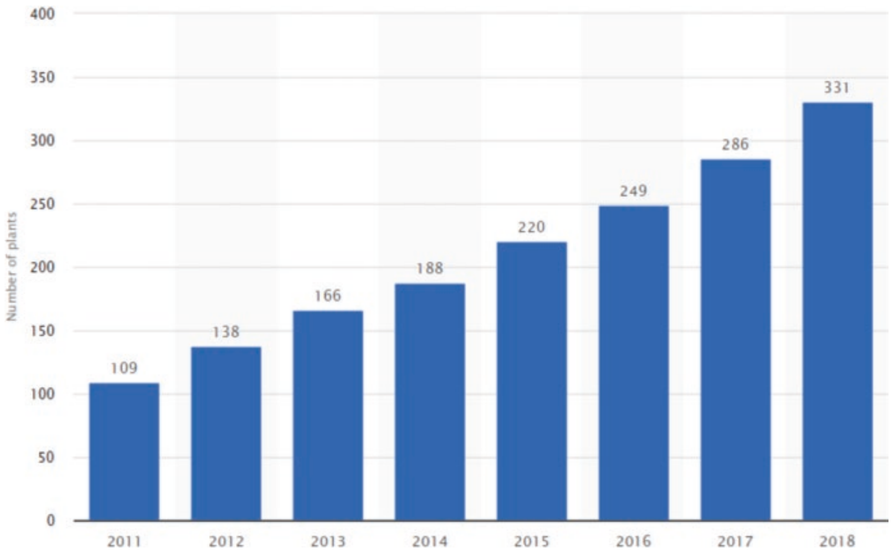

Fig. 6.14 Number of waste incineration plants in China from 2011 to 2018 [40]

Due to the limitation of landfill sites in the urban area, China began to apply incineration to manage the waste to generate electricity. The volume of waste generated in China had been continuously rising; the number of waste incinerating to energy power plants in China was about 331 in 2018 (Fig. 6.14) [40]. Incineration is recommended to the cities that have limited space for waste disposal facilities, thus incineration could reduce the waste volume and need for landfill sites. On the other hand, incineration is restricted by high costs and potentially toxic gas emissions. In China, municipal solid waste incineration technology was established at the end of the 1980s and rapidly developed in the 1990s [43]. Since the incineration technology would emit toxic gases during the process, this may cause air pollution and risk to human health. Therefore, waste incineration can be utilized on a large scale in the short term to govern the urgent waste problems faced in China [41].

6.2.2.2 Waste Management in India

India has contributed 12% of global municipal solid waste generation. With the continuously growing population, waste generation in the country is anticipated to increase in the coming decade [44]. In India, an estimated 67 million tons of food is wasted every year [45]. Only about 75–80% of the municipal waste is collected, and out of this, only 22–28% has undergone waste treatment. The remaining municipal waste is placed at the dump yards [46]. The hierarchy of sustainable waste management for India and other developing nations is different from the standard hierarchy of sustainable waste management (Fig. 6.15). India has carried out different types

Fig. 6.15 The hierarchy of sustainable waste management for India and other developing nations [47]

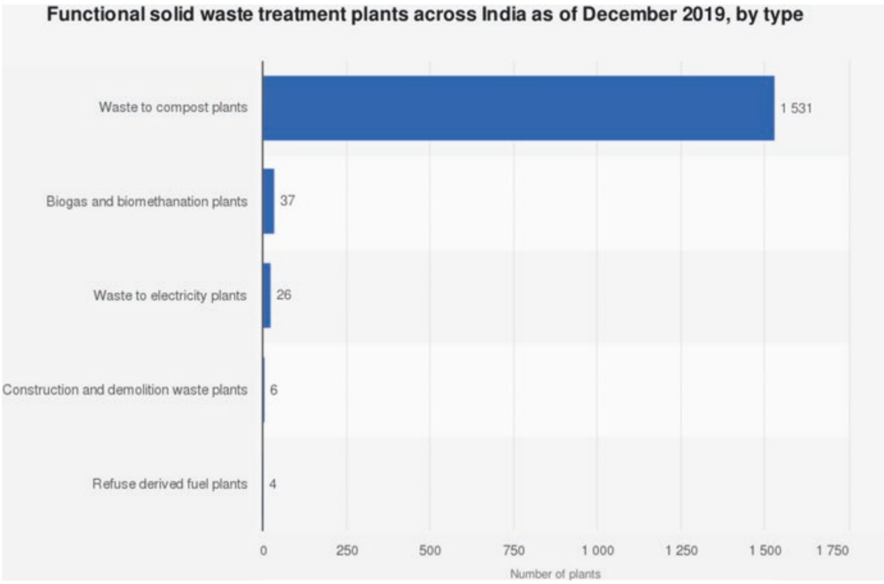

Fig. 6.16 Functional solid waste treatment plants across India as of December 2019, by type [44]

of waste management to manage the waste generated from the country (Fig. 6.16). The waste to compost plant was widely applied in India to manage the waste in 2019.

In 2019, there were 378 landfills in the state of Madhya Pradesh in India, which was the highest number compared to any state [44]. However, open landfills can bring on negative effects on the environment and public health such as the development of methane and global warming [45]. Since waste generation in India keeps growing, the land requirement for landfills also increasing. More than 90% of waste in India is assumed to be treated in an unsatisfactory manner. Engineered landfills are practiced in India to manage the waste appropriately. Properly managed engineered landfills should take over the dumps in India to protect the environment from pollution [48].

There are some challenges and limitations for India to apply the best and the most appropriate methods for waste management such as lack of knowledge in solid waste management, low budget, and lack of strategic municipal solid waste plan. To overcome the poor waste management in India, some proper ways can be implemented such as strong authority is needed to regulate waste management, long-term waste management planning is required, and provide professional training on waste management [48].

6.3 Current Practices Adopted for Composting of Organic Waste

6.3.1 Type of Composting

Various types of composting methods can be applied for waste treatment such as aerobic composting, windrow composting, aerated static pile composting, vermicomposting, and in-vessel composting. Those methods are commonly used to generate biomass or energy, and different methods will have their operation process; the waste removal efficiency depends on the composting condition. The toxic gases emitted from the composting need to be controlled to prevent air pollution. Various studies had been conducted on the type of composting for waste management.

6.3.1.1 Aerobic Composting

Aerobic composting is defined as a process of organic waste treatment by aerobic microorganisms in the presence of oxygen [49]. Neklyudov et al. [49] stated that the efficiency of composting stages depends on a variety of parameters, including aeration, temperature, moisture content, pH, and composition of the mixture to be composted. Aerobic compost under the correct conditions creates a lot of heat, which helps to kill all the pathogens. Aerobic compost reduces the biomass to usable compost faster than its anaerobic, and the decomposition will not smell when adequate oxygen is present [50].

Organic waste that undergoes aerobic composting will produce antibiotic resistance genes that will diffuse into other environmental media and create potential environmental health [51]. The functional membrane covering is applied on the aerobic composting to prevent the diffusion of microorganisms, dust, and aerosols into the pile to the exterior environment [52]. Ma et al. [52] mentioned that functional membrane covering not only blocks the pathogens diffuse into the ground but also prevents external conditions such as rain and ultraviolet light.

Household waste such as food waste, vegetables, and fruits can be composted using aerobic composting [53]. When 60% of cassava peel produced by the industrial waste is mixed with 40% organic waste in aerobic composting, it has a high reduction of waste and produced a high C/N ratio [54]. Dewilda et al. [54] mentioned that a high C/N ratio will enhance the composting speed and the amount of material reduced during composting with the presence of bio-activators to remodel organic material.

6.3.1.2 Windrow System

Windrow composting is conducted by placing raw materials in long narrow piles or windrows, which are turned regularly [31]. The purposes of turning carried out in the windrow composting are to aerate the windrow, avoid overheating, and mix the waste in order (Fig. 6.17) [5]. Although this method is difficult to operate and high cost, it increases the composting speed and retains heat [31].

Windrow composting is more suitable for substrates with adequate free air space. Therefore, substrates such as food waste and animal waste are not suitable to use for this method because those substrates need more bulking agents that may cause high production costs [4]. Windrow composting will give a high burden to the environment such as global warming. In the process of windrow composting, it consumes a large volume of diesel and emits a large amount of toxic gases into the atmosphere, thus global warming will occur, which is shown in Fig. 6.18 [55].

6.3.1.3 Aerated Static Pile Composting

Aerated static pile system is a variation to windrow system, in which the air is forced through a pile using aeration pumps [4]. The air is either blown or sucked through the pile to provide aeration and to control the temperature (Fig. 6.19) [5]. Aeration will speed up the process; therefore, less land area is needed [4].

The passively aerated static pile composting is applied to the organic food waste in Brazil. The compost produced from the aerated static pile composting had a high specific surface area, thus enhancing the adsorption capacity of the compost [56]. Lima et al. [56] found that the pH value of the compost produced from the static composting is 6.4, which is an acidic solution; however, it is almost near to the neutral condition.

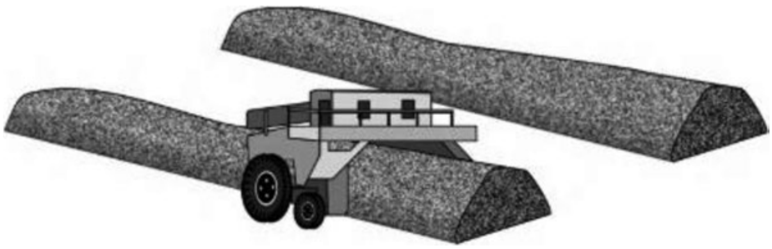

Fig. 6.17 Windrow system [3]

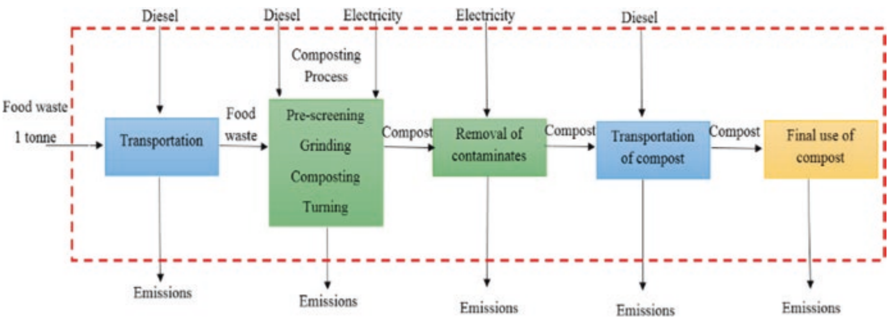

Fig. 6.18 Windrow system boundary [55]

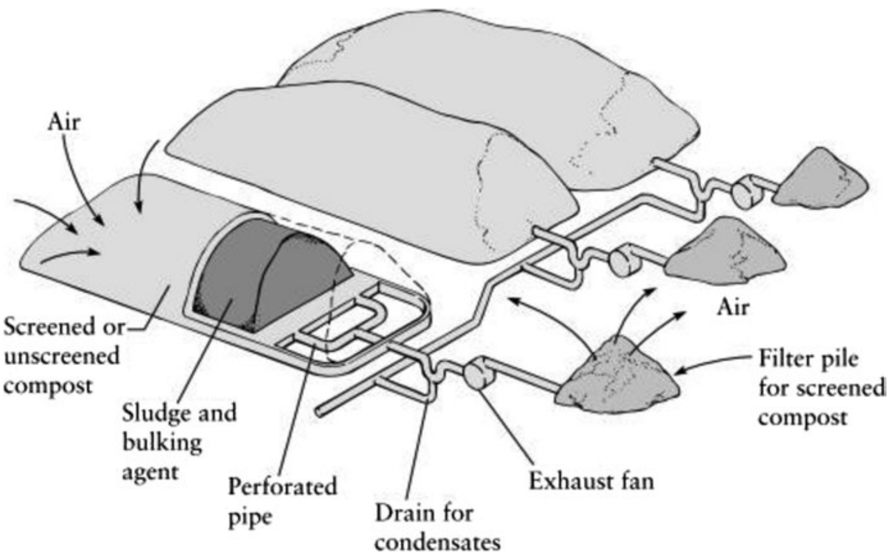

Fig. 6.19 Aerated static pile composting [37]

Fig. 6.20 In-vessel composting in rotary drum composter [4]

6.3.1.4 In-Vessel Composting

In-vessel composting is a high-technology method in which composting is conducted within a fully closed environment (Fig. 6.20) [4]. It is used to protect the composting materials and control environmental emissions and public health [5]. It depends on a variety of forced aeration and mechanical turning techniques to enhance the composting process [31].

In Korea, chicken manure mixed with sawdust and different ratio of rice husk biochar was added into the in-vessel composting [57]. Chung et al. [57] found that the waste with 10% of biochar produced less heavy metal content in the final product. The decrease of ammonium ions is due to the decrease of available ammonia in the compost materials. With the large amount of biochar, there is a large amount of ammonium ions reduction due to the strong adsorption characteristics of biochar along with nitrobacteria activity [58].

6.3.1.5 Vermicomposting

Vermicomposting is a method that uses earthworms to transform energy-rich and complex organic substances into a stabilized humus-like product [4]. Earthworms can degrade practically all kinds of organic matter by feeding on them [31]. The presence of heavy metals will hinder the vermicomposting process through the process of bacterial inhibition and alleviate the reproduction capacity of earthworms under metal stress [59]. The extracellular polymeric substance secreted by earthworm and microbial communities associated with vermicomposting tends to arrest the mobility of metals [60]. This forms organic metallic complexes, thus the heavy metals are reduced [59].

When the corn cob waste was undergone the vermicomposting process, the organic matter was decreased due to the earthworms used it for their metabolic and respiratory activities [61]. Castillo-Gonzalez et al. [61] found that the C/N ratio also reduced as a result of the carbon loss in microbial respiration and the addition of biological residue rich in nitrogen produced by earthworm.

6.3.2 *Co-composting as an Approach for Effective Biodegradation of Organic Waste*

Co-composting is one of the methods to enhance the nutrients or compositions of the substrates by mixing with other substrates. When the substrates are mixed, they produce good quality fertilizer or composting products that can be used for agriculture or plantation.

6.3.2.1 Co-composting of Food Waste with Other Substrates

Food waste is not favored for composting due to high humidity in the waste can cause anoxic conditions [62]. The food waste can generate a large amount of leachate and affect the composting process if without any co-compositing due to high moisture content and nutrient content in the food waste [63]. The food waste is used as co-composting with sewage sludge in the ratio of 1:2.7 through an aerobic composting process [64]. Chen et al. [64] explained that 15 mg of antibiotics was added into the sample, there was a high reduction of C/N ratio from 20.7 to 11.6. However, if a large amount of antibiotics were added to the sample, it would generate a higher C/N ratio in the final product due to the development of antibiotic resistance in the microorganism.

Eighty-five percent of food waste and 15% of wheat straw were added together through the in-vessel composting to produce a good quality of compost material [62]. Chen et al. [65] mentioned that the mixture of peat and kitchen waste such as Chinese white cabbage, cabbage, and banana peel had a low C/N ratio, which was less than 2 in aerobic and anaerobic composting. Thus, the composting material was incompatible. Zhang et al. [63] found that the ammonia produced from the mixture of kitchen waste and garden waste was low due to the presence of garden waste, which improved the C/N ratio and biodegradation efficiency in composting process.

6.3.2.2 Co-composting of Manure with Different Substrates

Chicken manure has a large amount of nitrogen content but poor in carbon, thus a low C/N ratio, which restricts the composting process [66]. The raw materials of banana pseudostem, mushroom media waste, and chicken manure were mixed in the ratio of 1:2:1; C/N ratio was the lowest compared to other mixed compositions [67]. Islam et al. [67] stated that mushroom media waste could absorb the nitrogen from the manure due to strong adsorption capacity, thus large amount of mushroom media waste would result in high reduction of the C/N ratio.

The mixture of chicken manure and cow manure in the composting process was the most effective to alleviate the ammonia emission [68]. Hwang et al. [68] mentioned that reduction of ammonia emission might improve the nutrient of the compost, thus the combination of chicken manure and cow manure in the composting process could generate better quality of compost. Another type of manure that is used in the composting method is pig manure. There were no negative effects on the maturity of the end product in the mixture of pig manure, sawdust, and diatomite [69]. Ren et al. [69] stated that diatomite was added into the composting to enhance nitrogen conservation and increase the quality of the end product, thus the C/N ratio of the mixture was lower than 20, which is safe for land utilization.

6.3.2.3 Co-composting of Rice Straw with Different Substrates

The application of a Fenton-like process in the composting of rice straw and sediment could accelerate the maturity of composting, thus it had low C/N ratio. There are various types of heavy metals in composting such as cadmium, chromium, zinc, copper, and lead [70]. Chen et al. [70] stated that cadmium was the highest reduction of heavy metals after 50 days of co-composting process in the mixture of sediment: rice straw: vegetables: bran with the ratio of 25:26:7:6. However, zinc did not have any significant effect in the co-composting process.

The C/N ratio of the rice straw and rabbit manure was in the range of 20–30, which indicated good composting effects [71]. Li-Li et al. [71] mentioned that the germination index of rabbit manure and rice straw was higher compared to the mixture of rice straw and mushroom residue, thus the mixture of rabbit manure and rice straw was more suitable for the growth of seeding in the composting process. The ratio of cow manure and rice straw was 2.5:1 applied in the aerobic composting. Due to the usage of carbon and nitrogen by the microorganisms for energy production and growth, thus the C/N ratio was decreased in the composting process [72].

6.3.2.4 Co-composting of Olive Waste with Various Substrates

Olive waste is one of the wastes that can be composted through the composting process. Various substrates can be mixed with olive waste to produce better quality of compost. The olive waste was mixed with the poultry manure and green waste in the composition of 51.72%, 20.68%, and 27.58%, respectively, through windrow composting [73]. Bargougui et al. [73] mentioned that the C/N ratio was decreased to less than 10 due to the decreased of total carbon content and increased of nitrogen content. In the batch bioreactor, 50% of olive mill solid sludge was mixed with 50% of green waste, the decomposition rate was more than 62% [74]. Bouhia et al. [74] demonstrated that this mixture has high oxidation of organic matter and good degree of degradability. Bouhia et al. [74] also explained that the mixture of olive mill solid sludge and green waste could reduce the lipid content and polyphenol content by 81% and 85%, respectively.

6.4 Black Soldier Fly Design and Control

*6.4.1 Black Soldier Fly Species (***Hermetia illucens***)*

Hermetia illucens which is known as black soldier fly is used as a waste-composting agent in the composting application. The life cycle of the black soldier fly is short, and the composting happens during the larval stage. The substrates used to feed the black soldier fly larvae must consist of different nutrients such as protein, carbohydrates, and lipid, and substrates with sufficient nutrients will enhance the growth of black soldier fly. The black soldier fly larvae can be used as waste treatment through the composting method. The black soldier fly larvae should be reared at optimum conditions, thus more waste can be reduced. Figure 6.21 shows different units of the black soldier fly treatment system.

6.4.1.1 Geographical Distribution of Species

Soldier fly or *Stratiomyidae* is the family of flies, *Hermetiinae* is one of the sub-family of *Stratiomyidae* [76]. In the past, five genera had been discovered under the sub-family of *Hermetiinae* such as *Chaetohermetia, Chaetosargus, Patagiomyia, Notohermetia*, and *Hermetia*. Recently, a new genus has been discovered under *Hermetiinae*, which is *Apisomyia* [77]. Black soldier fly or *Hermetia illucens* is the species of *Hermetia* (Table 6.9). *Hermetia illucens* has pale, translucent spots at the base of the abdomen that make it appear petiolate during flight [76]. The black soldier fly can be found in nature worldwide in the tropical and sub-tropical areas between the latitudes of 40°S and 45°N (Fig. 6.22) [75]. The dynamic population genetic history of a cosmopolitan dipteran of South American origin is shaped by striking geographical patterns and spread to other regions or countries such as Asia, Europe, and Africa [78].

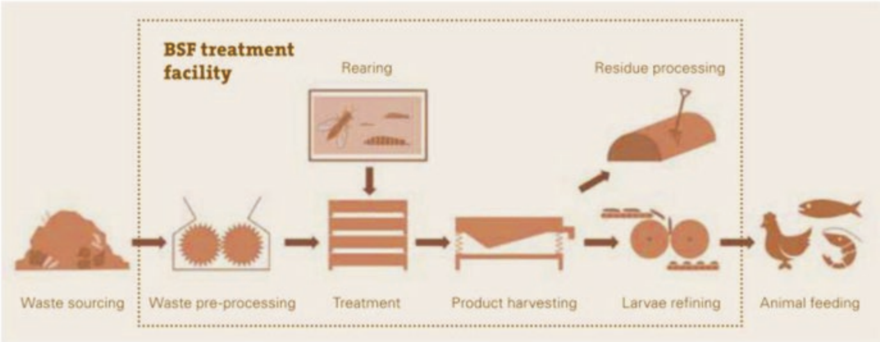

Fig. 6.21 Different units of the black soldier fly treatment system [75]

Table 6.9 Taxonomic classification of *Hermetia illucens*

Kingdom	Animalia
Phylum	Arthropoda
Class	Insecta
Order	Diptera
Family	*Stratiomyidae*
Sub-family	*Hermetiinae*
Genus	*Hermetia*
Species	*Illucens*

Fig. 6.22 Distribution area of *Hermetia illucens* [75]

6.4.1.2 Anatomy and Life Cycle

The black soldier fly is a small, harmless insect that can overcome agriculture's growing problems such as the high cost of animal feed and disposal of a large amount of animal waste or food waste [8]. There are five main stages in the black soldier fly life cycle such as egg, larva, prepupa, pupa, and adult stages, with a total life span of 45–48 days. The longest phases of the life cycle are the larva and pupa stages, whereas the egg and adult stages are relatively short (Fig. 6.23) [79]. The female black soldier fly lays at least 400–800 eggs close to the decomposing organic waste, which is small, dry, and sheltered cavities [75].

The anatomy of the black soldier fly in the larval stage is that its head is small and narrower than the body possibly for burrowing [80]. The larvae are dull, whitish with a small, projecting head containing chewing mouthparts [7]. The larva replaces its mouthpart with a hook-shaped structure, which is used to easily move out from the food source toward a protected environment when transforming into prepupa [75]. In the adult stage, the black soldier fly has a transparent window on the first abdominal segment that protects its internal anatomy from the outside environment and as a skeleton, which provides support and allows for movement. The female black soldier fly is larger than the male black soldier fly although there is no obvious external sexual dimorphism [80]. Figure 6.24 shows the anatomy *of Hermetia illucens* at each stage.

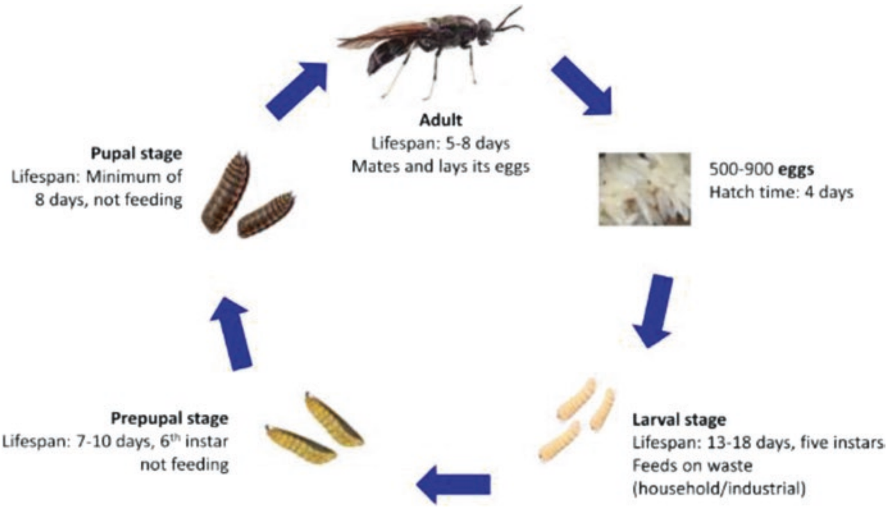

Fig. 6.23 Life cycle of the black soldier fly [79]

Table 6.10 Optimum conditions for the breeding and rearing of black soldier fly

Parameters	Optimum value/condition	References
Humidity	60%	[84]
	33.2–60%	[85]
	60%	[86]
	70%	[8]
Temperature	25–30 °C	[87]
	30 °C	[88]
	35 °C	[8]
	24–30 °C	[75]
	30 °C	[89]
Light intensity	Sunlight	[85] [84]
	110 µmol m^2 s^{-1}	[90]
	Mix of LED	[83]
pH	4.0/9.5	[91]
	6.0/8.0	[92]

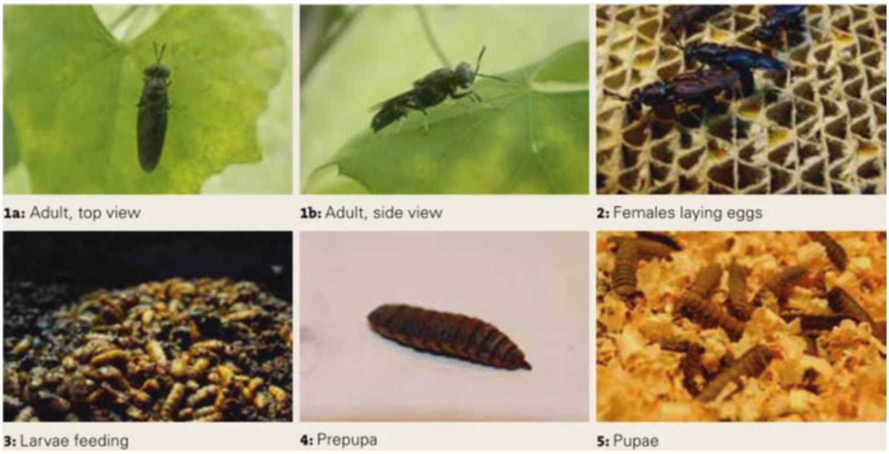

Fig. 6.24 Life stages and anatomy of *Hermetia illucens* [75]

6.4.1.3 Feed Characteristics

The larvae of the black soldier fly may consume organic material, including decomposable byproducts and wastes, for development until they reach the stage of prepupae [11]. Feeding only occurs during the larval stage, whereas in the adult stage, the black soldier fly relies only on the body fat stored from the larval stage [8]. The black soldier fly larvae can be fed with various substrates or organic wastes such as food waste, poultry manure, sludge, and green waste [81]. The black soldier fly larvae need to consume sufficient nutrients such as protein and lipid for growth and store those nutrients for the adult stage [11].

High protein in a substrate could contribute to the rapid growth of black soldier fly larvae [81]. The growth of black soldier fly larvae not only depends on the content of protein and fat in the substrates but also depends on the C/N ratio of the substrates [82]. The small size of substrates allows the larvae to access the nutrients easier because larvae do not have chewing mouthparts [75]. Volatile solid in the substrates affect the growth of the larvae, where the black soldier fly larvae do not grow well if the volatile solid in the substrate is low [81]. The presence of water and sugar in the substrates could affect egg production and enhance the oviposition period and adult lifespan, proposing that energy is needed for mating and egg laying in both females and males black soldier fly [83].

6.4.2 Factors That Affect the Growth of **Hermtia illucens**

Various factors need to be considered when rearing the black soldier fly; those factors will affect the growth and performance of black soldier fly such as pH, relative humidity, temperature, light intensity, and moisture content of substrates. The optimum condition must be determined; thus the black soldier fly can grow well and perform well in the reduction of waste. Table 6.10 shows the optimum conditions of pH, light intensity, relative humidity, temperature, and moisture content of substrates for rearing the black soldier fly larvae conducted by various researchers.

6.4.2.1 Humidity

The relative humidity is critical for captive growth and reproduction of the black soldier fly [8]. Low relative humidity would cause water loss through the egg membrane and further desiccation [90]. When the relative humidity was 30%, only 6.84% of the egg had enclosed and took a long time to enclose. However, 60% and 70% relative humidity had almost the same enclosure time, which is shorter than 30% relative humidity [84]. Thus, Holmes [84] mentioned that the number of egg enclosed and adult emergence increased when the relative humidity was increased until 70%.

Eighty percent of oviposition occurred when the humidity was greater than 60% [93]. In the black soldier fly breeding structure, the optimum relative humidity was in the range between 60.4% and 33.2% [85]. Holmes [86] stated that the egg enclosure and adult emergence increased with increasing relative humidity, while the development time decreased with rising relative humidity. When the relative humidity was low, the mortality was high due to high post-feeding occurred during the development period. When the relative humidity was 60%, the duration time of egg enclosure was 71 h, and the percentage of egg enclosure was 72.74%. The development of the black soldier fly was high at 70% humidity [8]. Bullock et al. [8] mentioned that the rate of weight loss for the black soldier fly increased with the decreasing relative humidity. Therefore, the optimum relative humidity that allows for the breeding and rearing of the black soldier fly is 60% relative humidity.

6.4.2.2 Temperature

Temperature is one of the factors that affect the growth, immaturity survival, adult lifespan, and population growth parameters [89]. The higher the temperature, the shorter the duration time for the egg enclosure, where 18 °C had the highest number of eggs that successfully enclosed [84]. Tomberlin et al. [88] also mentioned that the higher the temperature, the shorter the time of the larval development. Shumo et al. [87] stated that the development time of larvae and pupae was decreased with the increasing temperature. The optimum temperature range for larval development and adult emergence was 25–30 °C. The black soldier fly that is fed with spent grain had less development time of larval stage at 30 °C, which was 16.1 days. Shumo et al. [87] also mentioned that with the increasing temperature, the longevity of adult black soldier flies decreased. The adult longevity of the male soldier fly was 15.9 days at 30 °C, which is shorter than the male soldier fly at 27 °C, which was 17.4 days. Male black soldier fly had longer adult longevity compared to female black soldier fly at any temperature [88].

The optimal temperature that allowed the black soldier fly larvae to consume the food was 35 °C [8]. Bullock et al. [8] stated that the larvae would become inactive and survival would decrease when the temperature was less than 10 °C and higher than 45 °C. The time development of black soldier fly larvae in grain was the shortest when the temperature was 32.2 °C [94]. Dortmans et al. [75] stated that the ideal temperature for black soldier fly to develop is between 24 and 30 °C, where if high temperature the larvae would crawl away from food and if low temperature would slow down the metabolism. The percentage of egg enclosure was 70% and had the shortest development time which is 2.5 days at 35 °C. However, the life spans of adult black soldier fly were the shortest which is 4 days at 35 °C. Thus, the optimum temperature for the growth of black soldier fly was at 30 °C, which had high survival percentage of larvae [89]. Therefore, the optimum temperature that is suitable for the breeding and rearing of black soldier fly is between 25 and 30 °C.

6.4.2.3 Light Intensity

Direct sunlight was recommended for the black soldier fly breeding [85]. The longer the time exposed to the light, the shorter the time for the egg to enclose, where the eggs exposed to the sunlight for 12 h took less time to enclose. When those eggs did not expose to daylight, they would not develop successfully into pupae or adults due to post-feeding [84]. Holmes [84] revealed that a higher proportion of mortality would occur in the post-feeding stage because the larvae consumed the fat from their body and water loss from respiration. However, larvae would find a shaded environment and away from the sunlight [75].

Eighty-five percent of mating activity occurred in the morning with the light intensity of 110 μmol m^2 s^{-1} [90]. The mating activity would decrease when the light intensity was higher than 110 μmol m^2 s^{-1}. However, the mating activity was decreased at least 39% under quartz-iodine lamp compared to the effect of sunlight [95]. Light is not the main factor that influences egg production but is still observable in obtaining high quantity of eggs. Macavei et al. [83] demonstrated that the mix of LED such as ultraviolet: blue: green in the ratio of 1:1:3 had a longer oviposition period and enhanced egg laying compared to white LED and neon light.

6.4.2.4 pH

The percentage of larval mortality was low in acidic (pH 4.0) and basic (pH 9.5) conditions, which were 3.5% and 3.1%, respectively [91]. Meneguz et al. [91] stated that the black soldier fly larvae were capable of resisting and manipulating the acidic and basic environment. However, the percentage of emergence was the highest in the acidic (pH 4.0) environment, whereas the percentage of emergence was the lowest in the basic (pH 9.5) condition [91]. Ma et al. [92] stated that the optimum pH value for the growth of black soldier fly was slightly acidic (pH 6.0) and slightly basic (pH 8.0). Male black soldier fly had higher adult longevity at any pH value compared to the female black soldier fly.

6.4.2.5 Moisture Content

The moisture content of the substrates could affect the growth of black soldier fly. The growth period of the black soldier fly larvae was the shortest with a moisture content of 45%. The substrates with 45% moisture content had emitted 22% of carbon dioxide, which was higher than substrate with 75% moisture content, thus the substrate with 45% moisture content had a high growth rate and short growth phase [96]. When the food waste with 80% moisture content, it had a faster growth phase rate and achieved the maximum larval weight in the short period due to shortening of the production time. However, the moisture content would not affect the survival rate of black soldier fly larvae [97]. The substrates should have sufficient moisture content between 60 and 90%, thus the larvae could ingest the food [75].

6.4.3 Feeding Substrates on Black Soldier Fly

Black soldier fly larvae can feed various types of organic wastes such as animal manure, food waste, and green waste [8]. The black soldier fly larvae would spend more time developing when fed with organic wastes, which balance in nutritional contents of the organic waste [98]. The combination of diet help to increase the metabolism and the larvae become more active [8]. Those substrates rich in protein and carbohydrates result in good larval development [75]. Table 6.11 shows the growth performance of the black soldier fly larvae in single and mixed substrates.

Table 6.11 Growth performance of black soldier fly larvae in single and mixed substrates

Substrates	Larval development (days)	Prepupae weight (g)	Survival rate (%)	References
Single substrate				
Food waste	14	0.212	87.2	[81]
	–	–	92.6	[99]
	–	–	90.15	[10]
Vegetable	52	0.015	–	[98]
	48.33	0.084	46.0	[100]
Banana	–	–	100	[12]
Duck manure	22	0.0619	79.6	[101]
Poultry manure	14	0.164	92.7	[81]
House manure	50	0.015	–	[98]
Rice straw	22	0.0415	73.9	[101]
Poultry feed	14	0.251	93.0	[81]
Animal feed	–	–	76.7	[99]
Chicken feed	42	0.082	–	[98]
Compost	22	–	–	[102]
Piggery	19	–	–	[102]
Tofu dreg	35	0.052	–	[98]
Spent coffee grain	35	–	97.66	[103]
Spent coffee	–	17.5	98.6	[104]
Dough	–	19.5	83.3	[104]
Sewage sludge	–	–	46.65	[10]
	16–21	0.137	81.0	[81]
Mixed substrates				
Substrates	Larval development (days)	Prepupae weight (g)	Survival rate (%)	Reference
Fruit & vegetable	36.67	0.094	59.83	[100]
	28	0.218	90.7	[81]
Chicken feed & cow dung	30.1	0.055	96.6	[82]
Abattoir waste & fruit & vegetable	12	0.252	96.3	[81]
Duck manure & rice straw	22	0.0614	76.2	[101]
Sewage sludge, palm decanter & fermented maize straw	–	–	93.0	[99]
Brewer's spent grain & Brewer's yeast	8	0.1186	99.0	[103]
Sewage sludge and palm kernel expeller (3:2)	12	–	–	[105]
Spent coffee: Dough (1:1)	–	0.23	81.16	[106]
Fermented coconut endosperm waste: Soybean curd residue (3:2)	19	–	–	[107]

6.4.3.1 Single Substrates

Grained-reared larvae required less time to complete the larval development, whereas pork-reared would require more time to complete the larval development [94]. When the black soldier fly larvae were placed at the compost, the percentage of egg enclosure was 65% and had less period of larval development compared to the piggery. There was absence of egg enclosure from the poultry and sheep waste due to the depletion of nutrients [102]. The black soldier fly larvae fed with the tofu dreg had spent less development time with the feed rate of 12.5 mg/larva/day [98]. Lalander et al. [81] explained that the black soldier fly larvae in the abattoir waste had the highest survival rate, which is 101.5%, and the duration time for the first prepupae to occur was 12 days. When the feed rate was increased from 27 to 70 g/day, the larval development was decreased from 30.39 to 25.84 days, while the adult longevity rose from 9.96 to 13.64 days. However, there was high percentage of mortality which is 29% when the larvae were fed with a feed rate of 70 g/day [108].

When the black soldier fly larvae were fed with the fruit, they took longer time for the larval development, which was 52 days due to the fruit contains low protein content, which was 0.4 g/100 g of food waste. However, the black soldier fly fed with fruit had the highest adult emergency, which was 90.12% because the fruit contained large amount of carbohydrate which was 8.9 g/100 g of food waste [100]. Fitriana et al. [99] stated that the survival rate was 92.6% when the black soldier fly larvae were fed with the food waste, whereas the survival rate was 76.7% when the black soldier fly larvae were fed with animal feed. When the duck manure was used as a substrate to feed the black soldier fly larvae, the survival rate was the highest which was 79.6%. On the other hand, the survival rate was the lowest, which was 73.9% when the rice straw was used as a substrate to feed the black soldier fly larvae [101].

Sewage sludge had lower survival rate compared to food waste [10]. This is because the carbohydrates in the food waste were higher than in the sludge [81]. However, some of the substrates are not suitable for feeding due to low nutrients and may affect the growth of black soldier fly larvae. Thus, the substrates should be mixed with other substrates to enhance the nutrients, and the black soldier fly larvae can gain sufficient nutrients from the substrates for growth. Table 6.11 represents the growth performance of black soldier fly larvae that fed with the single substrate. Romano et al. [104] revealed that the black soldier fly larvae fed with the spent coffee had the highest survival rate, which was 98.6%. However, the black soldier fly larvae fed with the dough had higher larvae and prepupae weight compared to other substrates. The dough had the lowest cellulose that able the larvae to digest, and the dough also contains balanced nutrients in protein: carbohydrate ratio, which enhanced the growth of black soldier fly larvae.

Table 6.12 Growth performance of black soldier fly larvae in microbial fermented substrates

In situ fermentation					
Substrates	Growth rate (g/day)	Protein yield (%)	Lipid yield (%)	Waste reduction rate (d/day)	References
Coconut endosperm waste with 0.02% of *Rhizopus oligosporus*	0.065	–	–	0.23	[110]
Coconut endosperm waste with 2.5% of yeast concentration	0.085	30	–	0.4	[111]
Coconut endosperm waste with 2.5% of yeast concentration	0.085	–	44.4	0.4	[112]
Coconut endosperm waste with 0.02% of *Rhizopus oligosporus* spore suspension	0.065	23	47	–	[113]
Ex situ fermentation					
Substrates	Growth rate (g/day)	Protein content (%)	Lipid content (%)	Waste reduction rate (d/day)	References
Coconut endosperm waste with 0.02% of *Rhizopus oligosporus* spore suspension	0.095	27	45	–	[113]
Coconut endosperm with 0.5% of bacterial consortium powder (fermentation period: 21 days)	0.065	39.0	–	0.31	[114]
Self-fermented coconut endosperm waste (fermentation period: 4 weeks)	0.039	15.0	57.95	0.019	[115]
Self-fermented coconut waste (fermentation period: 4 weeks)	0.0374	15.0	42.74	0.020	[116]
Fermented coconut waste: Soybean waste (5:0)	0.040	11.06	56.00	0.045	[109]
Coconut endosperm waste with 0.5% of *Rhizopus oligosporus*	0.094	–	–	0.4	[110]
Maize straw with *aspergillus oryzae* (1:4000)	–	41.76	30.55	–	[117]

6.4.3.2 Mixed Substrates

When the black soldier fly larvae were fed with fruits and vegetables, the larvae grew rapidly, which meant it took the shortest duration time to develop from larval stage to prepupae stage [100]. When the sewage sludge, palm decanter, and fermented maize straw were mixed and fed the black soldier fly larvae, they had the highest survival rate which was 93% [99]. The growth of prepupal was almost the same when the black soldier fly larvae were fed with dark manure and the mix of dark manure and rice straw. The black soldier fly larvae were selectively eating the dark manure, leaving the rice straw untouched [101].

Lalander et al. [81] stated that the mixture of abattoir waste and fruit and vegetable, and the larval development period was the shortest due to high protein and high volatile solid content in the mixture. The chicken feed and cow dung were mixed, the larval development period was 30.1 days, and the survival rate was 96.6% [82]. When the brewer's spent grain was mixed with the brewer's yeast, the development time of larvae was 8 days, which was the shortest compared to other substrates, and the survival rate was 99.0% [103]. On the other hand, Sideris et al. [103] found that the survival rate of the mixture of spent coffee grain and brewer's spent grain was 87.42%, which was the lowest compared to other substrates.

Fischer et al. [106] demonstrated that the spent coffee was mixed with the dough had the highest survival rate and total prepupae weight compared to the black soldier fly larvae fed with spent coffee or dough. Mohd-Noor et al. [109] indicated that the mix of self-fermented coconut endosperm waste with the soybean curd residue in the ratio of 3:2, respectively; the black soldier fly larvae fed with the substrates had the highest growth rate and larval weight, which were 0.070 g/day and 1.336 g, respectively. The lipid content in the black soldier fly larvae was also the highest which was 58.70% compared to other mixed substrates. Raksasat et al. [105] explained that the protein content in the blended substrates would raise when the proportion of palm kernel expeller increased, thus the larval growth could enhance. The presence of palm kernel expeller improved the nutritional balance in the larval feed. Table 6.11 represents the growth performance of black soldier fly larvae fed with the mixed substrates.

6.4.3.3 Microbial Fermented Substrates

Microbial fermentation is the process that improves the nutritional composition of the black soldier fly larvae feeding substrates through microbial modification [11]. The fermentation processes are done by various microorganisms and can be classified into two types based on the inoculation modes, which are in situ fermentation and ex situ fermentation. In situ fermentation happens when the microorganisms are added to implement the fermentation process simultaneously with the valorization of organic substrates by the black soldier fly larvae. On the other hand, ex situ fermentation is the organic substrates that are fermented at the beginning by the microorganisms before feeding to the black soldier fly larvae. Thus, microbial fermentation can lead to changes in the nutritional and biochemical quality of the feeding substrates, resulting in enhancing the growth of black soldier fly larvae. Table 6.12 shows the growth performance of the black soldier fly larvae in the microbial fermented substrates through the in situ fermentation and ex situ fermentation.

6.4.3.3.1 In Situ Fermentation

Wong et al. [110] had conducted an experiment on in situ fermentation, where the black soldier fly larvae were inoculating at the stage of fermentation. When 0.02% of *Rhizopus oligosporus* was inoculated in coconut endosperm waste, the black soldier fly larvae had the highest growth rate and total weight gained which were 0.065 g/day and 0.77 g, respectively. Wong et al. [110] stated that 1.0% of *R. oligosporus* in the coconut endosperm waste had shown the highest overall degradation which was 30%. However, the overall degradation of in situ fermentation was lower than ex situ fermentation because the in situ fermentation allowed the black soldier fly larvae to consume part of the introduced *R. oligosporus* cells together with coconut endosperm waste at the early stage of fermentation.

The growth rate was 0.085 g/day when the black soldier fly larvae were fed with fermented coconut endosperm waste inoculated with 2.5% of yeast concentration, thus the rearing time was the shortest, which was 13.5 days [111]. Wang et al. [112] mentioned that 2.5% of yeast concentration in the coconut endosperm waste had the highest overall degradation which was 53.43% compared to other yeast concentrations, as a result of the addition of yeast in assisting the digestion of coconut endosperm waste by the black soldier fly larvae. Wang et al. [112] also revealed that the highest lipid yield in the black soldier fly larvae was 49.4% at 1.0% of yeast concentration. The highest protein content found in the black soldier fly larvae was 35% when fed with fermented coconut endosperm waste inoculated with a 0.02% of yeast concentration.

The *Bacillus subtilis* was inoculated with the chicken manure, the material reduction rate was 40.5%, which was higher than chicken manure without inoculation of *B. subtilis* [118]. Xiao et al. [118] indicated that the black soldier fly larvae weight gain rate was 15.9%, thus the *B. subtilis* inoculums could accelerate the black soldier fly larvae growth and reduce the chicken manure accumulation. The *R. oligosporus* spore suspension had inoculated with the coconut endosperm waste through the in situ fermentation [113]. The highest growth rate of the black soldier fly larvae was 0.065 g/day at 0.02% of *R. oligosporus* spore suspension. The highest lipid and protein yields in the black soldier fly larvae were 49% at 1.0% inoculum size and 30% at 0.5% inoculum size, respectively [113].

6.4.3.3.2 Ex Situ Fermentation

Wong et al. [110] had also conducted an experiment on the ex situ fermentation, where the black soldier fly larvae were inoculated after the fermentation process had been done. When 0.5% of *R. oligosporus* was added inoculated in the coconut endosperm waste, the black soldier fly larvae had the highest growth rate and total weight gained, which were 0.094 g/day and 1.13 g, respectively. Wong et al. [110] mentioned that 0.5% of *R. oligosporus* in the coconut endosperm waste shown the highest overall degradation which was 44%. The overall degradation had decreased although the content of *R. oligosporus* in the coconut endosperm waste increased from 1.0 to 2.5%, as a result of the presence of the remaining population of *R. oligosporus* to conduct enzymatic activities was inefficient, hindering the fermentation process.

The maize straw was mixed with the *Aspergillus oryzae* in an inoculation ratio of 1:4000, the survival rate of black soldier fly larvae was 93% and the dry mass reduction was 48.41% [117]. Gao et al. [117] indicated that the weight of the black soldier fly larvae in fermented maize straw was lower compared to wheat bran due to the unbalanced nutrition in the maize straw, low protein content, and high cellulose content. The 0.5% of *R. oligosporus* spore suspension inoculated in the coconut endosperm waste through ex situ fermentation, and the 0.095 g/day growth rate had obtained. The ex situ fermentation had better growth performance than in situ fermentation, due to the development of *R. oligosporus* being hindered during the progress of the in situ fermentation [113]. The highest lipid and protein yield in the black soldier fly larvae were 47% at 1.0% inoculum size and 30% at 0.1% inoculum size, respectively. The ex situ fermentation had higher lipid productivity than in situ fermentation, thus ex situ fermentation had higher biomass values gained and growth rate of the black soldier fly larvae [113].

Mohd-Noor et al. [109] indicated that the self-fermented coconut waste without mixing with the soybean curb residue had the lowest protein yield which was 11.06%. However, it had the highest waste reduction rate compared to other mixed substrates. Norgren et al. [119] mentioned that the fermented pulp and paper biosludge was not suitable to use as feed for black soldier fly larvae because the growth of black soldier fly larvae and the waste reduction were low. The coconut waste had undergone different duration times of self-fermentation, and the coconut waste that had undergone 4 weeks of self-fermentation had the highest weight gain of larvae and growth rate which were 0.6727 g and 0.0374 g/day, respectively [116]. Noor et al. [116] stated that the medium at week 4 fermentation was matured where the nutrient level was the highest, whereas after week 4 fermentation the microbes in the medium died and the nutrient content in the medium decreased.

The coconut endosperm waste had undergone the 28 days fermentation period with the inoculation of 0.5% of bacterial consortium powder, and 0.053 g/day growth rate had been obtained which was the highest compared to other concentrations of bacterial consortium powder. However, when the coconut endosperm waste was fermented for 21 days with the inoculation of 0.5% of bacterial consortium powder, 0.065 g/day growth rate had achieved which was higher than 28 days fermentation period, and 39% protein yield contained in the black soldier fly larvae [114]. Wong et al. [114] indicated that the presence of bacterial consortium powder act as an ancillary exo-microbes in stimulating the fermentation process on the larval feeding medium to improve the growth of black soldier fly larvae and shortening the fermentation period to prevent the loss of the nutrient in the medium.

6.4.4 Black Soldier Fly System Design

A black soldier fly system is set up as a location for breeding and rearing of the black soldier fly from egg stage to adult stage. The surrounding conditions of the black soldier fly system such as humidity, moisture content, temperature, light intensity, and pH shall make sure in the optimum condition. The type of substrates that use to feed the black soldier fly will affect the growth of the black soldier fly due to different nutrient content contained in the substrates.

The black soldier fly was extracted to the cage contained organic waste that allowed the female black soldier fly for oviposition and the cage was exposed to the sunlight for mating activity [120]. The black soldier fly eggs were kept on the substances made of commercial chicken feed with 60% moisture, at a constant temperature of 28 °C, and 70% humidity [98]. The larvae were extracted and reared in a climate chamber with 25 °C, 60% relative humidity, and photoperiod 12:12 (L:D) [100]. The container that was used to store the larvae should cover with a black plastic sheet to protect the black soldier fly larvae from light disturbance [98]. The perforated black polytene was not only used to prevent direct exposure to sunlight but also used to prevent the loss of excessive moisture from the substrates [120]. Wood shaving could also be used to cover the container to prevent desiccation [100].

The container that breeds the larvae should be covered with nylon to prevent invasion by other insects [82]. The lid was also used to prevent the infestation of feeding materials by other insects and parasitoid attacks [98]. The perforated lid was recommended to allow aeration in the system, and mosquito net was used on the lid to prevent other insects from breeding [120]. Insect gum was used to prevent intrusion by predators [82]. When the larvae developed into prepupae, the prepupae were transferred and kept on the moist wood shavings in a dark cage to facilitate adult emergence [82]. Once they were developed into adults, they were located at room temperature, 25 °C, and 25% relative humidity for mating activity [100]. BioPod Plus Auto Harvesting Grub Composter is the bin that is used for the breeding of black soldier fly. This bin is weather and mold resistant and has a drip channel that diverts condensation and excess liquid away from the organic matter and for air ventilation [90].

The substrates that are prepared to feed the black soldier fly larvae shall be in specific particle size and have a moisture content between 60 and 90%. The waste quality used for feeding should be controlled; there are no hazardous materials and inorganic substances contained in the organic waste [75]. Dortmans et al. [75] stated

Table 6.13 Biomolecules present in the black soldier fly larvae

Substrates	Proteins (%)	Lipids (%)	Carbohydrates (%)	Chitin (%)	References
Fermented coconut endosperm waste	45.72	25.88	–	18.62	[122]
Food waste	9.9	84.5	4.8	–	[123]
Sewage sludge and palm kernel expeller (3:2)	–	17	–	–	[105]
Chicken feed	60.2	33.6	–	6.2	[124]
Vegetable waste	39.9	37.1	–	5.7	[124]
Supermarket waste	38.86	40.96	–	3.85	[125]
Solid aquaculture waste (45% relative humidity)	42.5	7.6	39.8	–	[126]

that the size of substrates should be reduced to 1–2 cm in diameter by using the shredder. This might help to speed up the bioconversion processing by the black soldier fly larvae to break the waste, and increasing the surface area promotes the growth of bacteria.

The larvae were reared on the hen feed with 62.5% moisture content [100]. If the moisture content was higher than 80%, the waste was mixed with other wastes to reduce the moisture content that was lower than 80% [75]. Liu et al. [121] had mixed the food waste and sawdust to reduce the moisture content, where the initial moisture content of food waste was 86.57%, and mixed with sawdust, the moisture content was reduced to 80.81%. If a large amount of waste was fed to the larvae, those unprocessed waste would generate heat through the bacterial activity; as a result, the environment was not suitable for larvae to survive. Whereas, a small amount of waste was fed to the larvae would cause a reduction of development speed [75].

6.4.5 Biomolecules from Black Soldier Fly

Biomolecules are the ions or molecules present in living organisms. There are four major types of biomolecules which are carbohydrates, lipids, nucleic acids, and proteins. Black soldier fly contains large amount of proteins, lipids, and other biomolecules, which are consumed from the substrates. Different amounts of biomolecules present in the black soldier fly larvae are shown in Table 6.13.

Figure 6.25 shows the average composition of biomolecules in mature black soldier fly larvae.

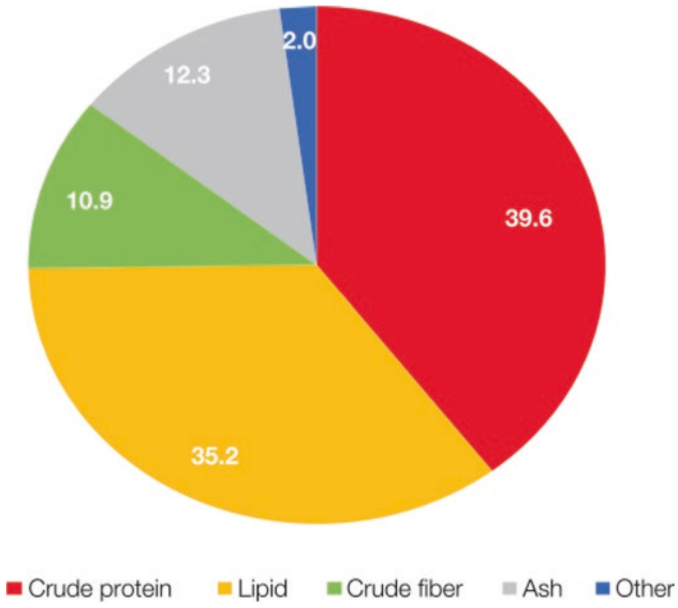

Fig. 6.25 Average composition of a mature black soldier fly larva (%DM) [13]

6.5 Waste to Valuable Biomass

The black soldier fly larvae can convert the organic waste into biomass through the composting method. Through the composting method, the organic waste will be reduced, and the composting product can be used as fertilizer for plantation and agriculture activities to enhance the growth and yield of the plant. The substrates that are used to feed the black soldier fly larvae are important because the black soldier fly larvae gain the nutrients such as protein and lipid from the substrates. The black soldier fly can be used as animal feed because it contains sufficient nutrients for the living organism to consume, thus enhances the growth of the living organisms. Other than that, the lipid that is obtained from the black soldier fly larvae can be converted into high-quality biodiesel or biofuel.

6.5.1 Black Soldier Fly Frass as Biofertilizer

Black soldier fly frass is the compost product from feeding the black soldier fly larvae with the substrates, and the substrates are converted into fertilizer to be used for plantation and agriculture. The frass can help to enhance the growth and the yield of the plant and reduce the use of the inorganic fertilizer in the agriculture field. Table 6.14 shows the characteristics of the black soldier fly frass fertilizer.

Table 6.14 Characteristics of black soldier fly larvae frass

Type of fertilizer frass	Parameter Total phosphorus (%)	Total potassium (%)	Total Kjeldahl nitrogen (%)	C:N (%)	Germination index (%)	References
Natural compost frass	–	0.081	6.01	6.99	–	[127]
Fresh frass	–	0.099	4.78	7.76	–	[127]
Composted black soldier fly frass fertilizer	0.50	0.29	3.61	10.7	86	[128]
Cow manure with black soldier fly larvae	0.96	1.95	1.87	18.78	115.21	[129]
Food waste with black soldier fly larvae	1.14	0.84	3.12	16.50	82.04	[10]
20% biochar and brewery spent grains	0.72	0.14	1.60	18.7	132	[130]

The aerated compost frass had higher germination index on the pak choi seeds compared to the fresh frass and naturally composted frass. The fresh frass had low germination index due to high concentration of phenols, while the naturally composted frass had low germination index due to excess nutrients or chitin in the frass [127]. Song et al. [127] demonstrated that 20% of fresh frass mixed with biochar had shown higher leaf number on the pak choi plants, same to 10% of naturally composted frass mixed with biochar and 40% of aerated compost frass mixed with biochar. Agustiyami et al. [131] reported that black soldier fly frass in 5%, 10%, and 15% had shown better growth performance in plant height and number of leaves of pak choi. The phosphorus and potassium contents on the pak choi were high because the organic fertilizer contained high essential nutrients for the plant to absorb for growth.

The black soldier fly larvae were fed with cow manure, the germination index was the highest compared to chicken manure and pig manure. The compost products of chicken manure and black soldier fly larvae with chicken manure were not suitable to be used as fertilizer because their germination index was lower than 80%, which were 8.9% and 23.81%, respectively [129]. Liu et al. [129] explained that low germination index due to high concentration ammonium ion and electrical conductivity in the final products, thus the final product was not suitable for plants as fertilizer. The combination of black soldier fly fresh frass and mineral fertilizer could enhance the growth of tomatoes, kales, and French beans in plants height, the number of leaves, and stem diameter. The vegetable yields were also the highest when the black soldier fly fresh frass was mixed with the mineral fertilizer [128]. Anyega et al. [128] indicated that the combination of black soldier fly fresh frass and mineral fertilizer had better performance in the growth and yield of vegetables as a result of lower C/N ratio and high germination index which were 10.7% and 86%, respectively.

Liu et al. [10] revealed that when the electrical conductivity increased significantly, the higher the reduction of organic matter. The food waste was composted together with the black soldier fly larvae, the electrical conductivity was increased sharply, thus high in reduction of organic matter. The electrical conductivity of final products was lower than 4000 μS/cm; therefore, it was safe to utilize in soil. Only the germination index of food waste and black soldier fly larvae was greater than 80%; hence, the final product produced from the food waste and black soldier fly larvae was mature and appropriate to use as fertilizer for plants [10]. The mix of 20% biochar and brewery spent grains had produced the highest frass fertilizer yield, which was 1.13 kg. The germination index of the frass fertilizer generated from the mix of biochar and brewery spent grains was greater than 80%, thus the frass fertilizer was safe to use as fertilizer and no phytotoxicity occurred [130]. The mix of food waste and sawdust was composting together with the black soldier fly and had generated higher germination index compared to without black soldier fly. The germination index of the final product was lower than 80%, which was moderate phytotoxicity because the presence of black soldier fly larvae addition could decrease the accumulation of volatile fatty acids and boost the ammonia transformation [121]. Liu et al. [121] explained that the germination index was lower than 80% due to lower pH and higher concentration of ammonium ions in the final product that could inhibit the seed germination.

6.5.2 Black Soldier Fly Larvae as Animal Feed

Black soldier fly larvae can be used as animal feed to feed the animals, the animals consume the nutrients such as protein from the black soldier fly larvae to allow them to have better growth performance. The black soldier fly larvae meal was combined with the fish meal had used to feed the pig. The black soldier fly has different compositions depends on the technology processing, harvesting, medium rearing, and age [132]. The final body weight gained by the pig was the highest when 100% of black soldier fly larvae meal was used to feed the pig [133]. Chia et al. [133] demonstrated that the dietary replacement of fish meal with the black soldier fly larvae meal can be allocated to enhance palatability of the diets due to sufficient consumption of digestible nutrients especially protein, which help in rapid growth. The black soldier fly meal was used as animal feed to feed the dog through in vivo and in vitro digestibility. Crude protein in the black soldier fly meal was higher than the venison meal [134]. Penazzi et al. [134] mentioned that the organic matter and crude protein digestibility in the estimated in vivo digestibility based on the in vitro digestibility were overestimated by up to 4.0% and 9.8%, respectively, compared with the in vivo methods.

Black soldier fly larvae oil and meal could be used as dietary energy, protein, and amino acids for hen growth and egg production. The soybean oil was replaced by the black soldier fly larvae oil, and there was no significant impact on the egg production and the growth of the hen [135]. However, Patterson et al. [135] demonstrated that 8% and 16% black soldier fly larvae meal was replacing the soybean oil and meal, the egg production of the hen was higher compared to the control sample. Black soldier fly larvae oil did not have any adverse effect on organ weights and intestine development. However, the increasing percentages of medium-chain fatty acids in adipose tissue of chickens were due to the presence of black soldier fly larvae oil [136]. Kim et al. [136] mentioned that the black soldier fly larvae oil could improve the medium-chain fatty acids in edible tissues, influence gut health, and enhance the antioxidant capacity in broiler chickens.

Elechi et al. [137] indicated that the black soldier fly prepupae were fed with the chicken mash, food waste, brewery waste, and fruit waste were safe to be consumed by the animal because the concentration of heavy metals contained in the black soldier fly prepupae did not exceed the maximum allowable limit used as animal feed. The quail were fed with the black soldier fly meal had better feed consumption and high egg production due to high intake of fat compared to the quail fed with the fish meal [132]. Astuti et al. [132] declared that black soldier fly can be used as a protein source without any adverse effect on the animal.

Table 6.15 Fatty acid methyl esters (FAME) profile of black soldier fly larvae

FAME composition (%)	Substrates			
	Blended sewage sludge and palm kernel expeller (3:2)	1.0% Yeast fermentation with coconut endosperm waste	Food waste	Food waste
Process	Base-catalyzed transesterification	Base-catalyzed transesterification	Base-catalyzed transesterification	Non-catalyzed transesterification
C10:0	4.48	1.3	2.1	2.2
C12:0	53.36	66.0	47.4	47.1
C14:0	12.52	14.4	8.2	8.0
C14:1	2.79	1.4	–	–
C16:0	9.89	6.6	14.4	14.6
C16:1	4.40	2.2	2.4	2.1
C18:0	1.23	0.4	2.8	3.3
C18:1	9.22	5.6	16.3	15.4
C18:2	2.11	2.3	6.3	7.2
Saturated fatty acid	81.48	88.7	74.9	75.2
Monosaturated fatty acid	16.41	9.2	18.7	17.5
Polyunsaturated fatty acid	2.11	2.3	6.3	7.2
FAME yield	–	–	93.8	94.1
Reference	[105]	[112]	[123]	[123]

Table 6.16 Fatty acid methyl esters (FAME) profile of black soldier fly larvae (continue)

FAME composition (%)	Substrates			
	Fermented white bran	Coconut endosperm and soybean curd residue (3:2)	0.5% mixed-bacterial powder with coconut endosperm waste	Restaurant waste
Process	Direct transesterification	–	–	–
C10:0	1.9	–	2.2	1.13
C12:0	41.5	0.35	63.1	18.89
C14:0	8.1	8.80	13.5	9.91
C14:1	–	–	–	–
C16:0	13.1	0.73	8.2	20.96
C16:1	2.0	1.64	2.7	6.45
C18:0	2.9	1.80	–	6.5
C18:1	10.6	40.81	8.3	22.54
C18:2	16.4	–	2.0	12.67
Saturated fatty acid	71.0	15.72	87.0	57.39
Monosaturated fatty acid	12.6	73.08	11.0	28.99
Polyunsaturated fatty acid	16.4	11.20	2.0	12.67
FAME yield	–	16.68	37.8	–
References	[139]	[107]	[122]	[138]

6.5.3 Biomass to Energy Production

Biomass is one of the renewable energy that is produced from the wastes such as food waste and animal waste. The biomass can be converted into different types of energy such as biofuel, biogas, electricity, and heat through the decomposition of the waste. Black soldier fly is used to decompose the waste through the composting process and produce biomass. The biomass that can be obtained from black soldier fly is biodiesel or biofuel which is produced from the fat or lipid of the black soldier fly. Wang et al. [138] mentioned that the black soldier fly with high content of lipid is a potential raw material for biodiesel production. Various parameters will affect the lipid yield from the black soldier fly such as type of solvent, extraction solvent, extraction time, and solute–solvent ratio (g/mL). Tables 6.15 and 6.16 show the fatty acid methyl esters (FAMEs) profile in the lipid extracted from the black soldier fly fed with different substrates.

The analysis of fatty acid methyl ester in the biodiesel is performed. Sixty-two percent monounsaturated fatty acids were determined in the biodiesel which the black soldier fly larvae fed with 4-weeks self-fermented coconut endosperm waste [115]. Mohd-Noor et al. [115] explained that high monounsaturated fatty acids result in high cetane numbers to the biodiesel. A high number of cetane numbers, the better the fuel burns within the engine of the vehicle, where better fuel combustion and quicker ignition [140]. Mohd-Noor et al. [115] demonstrated that low polyunsaturated fatty acid and high C18:1 would provide better biodiesel quality derived from black soldier fly larvae. The black soldier fly larvae were fed with the ex situ fermentation of *Rhizopus oligosphorus* inoculated with coconut endosperm waste produced high lipid yield and better quality of biodiesel. The black soldier fly larvae could be used as biodiesel due to the total amount of linolenic acid methyl ester (C18:2) was low [110].

The biodiesel production from the black soldier fly larvae grown on the food waste was performed through the base-catalyzed and non-catalytic transesterifications of black soldier fly larvae extract. The fatty acid methyl ester yields from the non-catalytic transesterification were 94.1%, which was higher than base-catalyzed transesterification [123]. Jung et al. [123] explained that the biodiesel production from the non-catalyzed transesterification was more valuable compared to the base-catalyzed transesterification because non-catalyzed transesterification did not produce the alkaline solution, and the MeOH and lipid were converted rapidly into biodiesel. The high yield of biodiesel could produce through direct transesterification with 60 min reaction time, 110 °C temperature, methanol/biomass ratio of 8:1 (mL/g), and DBU (1,8-diazabicyclo[5.4.0]undec-7-ene)/biomass ratio of 16:1 (mL/g) [139]. Nguyen et al. [139] indicated that the use of black soldier fly larvae could reduce the biodiesel production costs and the DBU-catalyzed direct transesterification is an ability and cost-effective approach for eco-friendly biodiesel production without any harmful chemical was used. The optimum lipid yield from the microwave-assisted extraction technique was 32.49% at condition 15 g/mL of solute to solvent ratio, 50 min extraction time, and 60 °C extraction temperature. The fatty acid compositions such as 22.54% oleic, 12.67% linoleic, and 6.45% palmitoleic acid were found in the extracted lipid and could be considered as a potential source for the production of biodiesel [138].

A high yield of fatty acid methyl ester was obtained from the black soldier fly fed with 0.5% mixed-bacteria powder concentration with coconut endosperm waste and 14 days fermentation period. The black soldier fly larvae-derived biodiesel contained 87% of saturated fatty acids and 13% of unsaturated fatty acids [122]. The mix of coconut endosperm waste and soybean curd residue in the ratio of 3:2 obtained high yield of fatty acid methyl ester which was 16.68%. In the fatty acid methyl ester profile, the content of monounsaturated fatty acid, saturated fatty acid, and polyunsaturated fatty acid were 73.08%, 15.72%, and 11.20%, respectively [107]. Lim et al. [107] explained that the polyunsaturated fatty acid was lower than 20% revealed the oxidation stability which would enable a long storing period for biodiesel. High saturated fatty acid could stiffen the oxidation stability of biodiesel, and high percentage of monounsaturated fatty acid was suitable for biodiesel. On the other hand, the cold flow of biodiesel with high saturated fatty acid would degrade due to the increase in viscosity and density.

Table 6.17 Case study of black soldier fly technology applications in various countries

Country	Case study	References
China	Immune responses in avian infectious bronchitis virus on living organisms	[141]
	Conversion of the municipal sewage sludge that contained heavy metals	[142]
	Transforming carbon dioxide into lipid for biodiesel	[143]
	Bioconversion-composting process	[144]
The United States	As soil amendment for soil bio-solarization	[145]
	Nitrogen-phosphorus-potassium values of the frass	[106]
	Attitude to the black soldier fly larvae as food	[146]
	Phosphorus digestibility as animal feed	[147]
Malaysia	Base-catalyzed transesterification process for extraction of lipid	[105]
	Acid-catalyzed esterification and base-catalyzed transesterification for extraction of lipid	[110]
	Response surface methodology	[148]
	Microwave-assisted extraction of black soldier fly larvae	[149]
	Hybrid treatment	[150]
South Korea	Converted biodiesel through non-catalytic transesterification	[123]
	Microwave-dried black soldier fly larvae meal for broiler diet	[19]
	Antimicrobial activity	[151]
Italy	Antimicrobial biomasses from lactic acid fermentation	[152]
	Fishmeal replacement in aquafeeds	[153] [154] [155]

6.6 Case Study of Black Soldier Fly Technology Application

Black soldier fly technology applications have been widely applied in many countries such as China, the United States, Malaysia, and other countries for waste management and waste to energy production. Black soldier fly technology is used for waste management due to its low cost and ease of operation. Various applications that utilized black soldier fly technology such as biofertilizer, biodiesel production, used as animal feeds, and composting process. Many kinds of research have been conducted on the black soldier fly technology to improve the quality product of compost materials, nutrients of black soldier fly, and biodiesel production. Table 6.17 represents the case study of black soldier fly technology applications in various countries.

6.6.1 China

Municipal sewage sludge may consist of various heavy metals that will affect the activity and growth of black soldier fly larvae. Cai et al. [142] had collected sludges from industrials and domestics, and the heavy metals in the sludges were analyzed by HNO_3–H_2O_2 digestion and inductively coupled plasma-optical emission spectroscopy (ICP-OES) analysis. The black soldier fly larvae were fed with sludge contained heavy metals would affect the survival rate. To enhance the growth and nutrient of the black soldier fly larvae, co-substrate was added with the sludge. The content of heavy metals in the bodies of black soldier fly larvae would increase during the conversion process, whereas the concentration of heavy metals in the treatment residue was low and considered safe to use as fertilizer. Cai et al. [144] had established a new bioconversion-composting process of golden needle mushroom root waste by using black soldier fly larvae to generate better quality of biomass and organic fertilizer through the process stages of black soldier fly larvae conversion and conventional composting.

Coronavirus is a virus that will infect the respiratory system of humans and animals. Zhang et al. [141] indicated that the young chickens infected with avian infectious bronchitis virus fed with the inclusion of black soldier fly larvae meal at 10% would improve their immune response, and the avian infectious bronchitis virus loads were reduced in the trachea and kidneys. The $CD8^+$ T lymphocyte proliferation was enhanced with the diet supplemental of black soldier fly larvae; therefore, the living organisms could defend against the avian infectious bronchitis virus infection. Pang et al. [143] had carried out the feasibility of transforming carbon dioxide into lipids for biodiesel by integrating the black soldier fly larvae bioconversion. The larvae that were fed with high volatile fatty acids would represent high levels of saturated fatty acids, thus a better quality of biodiesel was generated. This integrated process could produce clean energy by recycling carbon dioxide and organic waste.

6.6.2 The United States

The final products after composting the waste by using the black soldier fly larvae can be used as a soil amendment to improve the soil quality for plantation. Axelrod et al. [145] demonstrated that the use of black soldier fly larvae disgested residue could increase the carbon, C/N ratio, nitrogen, phosphate, potassium, and ammonium in the sandy loam and sandy clay loam. However, the black soldier fly larvae disgested spent pollinator hulls could be utilized in biosolarization and as soil amendments, which depend on the concentration and strategies. Thus, the application and environmental conditions should be carefully chosen to diminish the persistence of soil phytotoxicity.

The black soldier fly larvae fed with the blended substrates have better growth and survival compared to single substrates. Fischer et al. [106] indicated that the spent coffee mixed with the dough could have better growth for the black soldier fly larvae (Table 6.18). The frass compositions produced from the blended substrates such as nitrogen and phosphorus were higher compared to those single substrates, those compositions are essential for the frass to act as organic fertilizer (Fig. 6.26). The black soldier fly larvae were fed with the blended substrates that had high lipid

Table 6.18 Survival and productivity (mean ± SE) of black soldier fly larvae and prepupae when cultured with spent coffee, dough or an equal blend of these after 35 days

Production	Spent coffee	Blend	Dough
Gross production (g/day/m^3)	1.83 ± 0.58^b	5.51 ± 1.01^a	1.68 ± 1.00^b
Net production (g/day/m^3)	0.75 ± 0.58^b	4.42 ± 1.02^a	0.60 ± 1.01^b
Survival (%)	45.13 ± 10.2^b	81.16 ± 12.5^a	24.56 ± 4.76^c
Total larvae (g)	42.32 ± 13.61^b	127.42 ± 23.57^a	38.95 ± 23.32^b
Total prepupae (g)	2.56 ± 0.84^b	20.70 ± 3.29^a	15.40 ± 3.68^a
Total production (g)	44.89 ± 13.1^b	148.12 ± 20.44^a	54.35 ± 20.99^b

Different superscripted letters in each row indicate Significant differences ($p < 0.05$) [106]

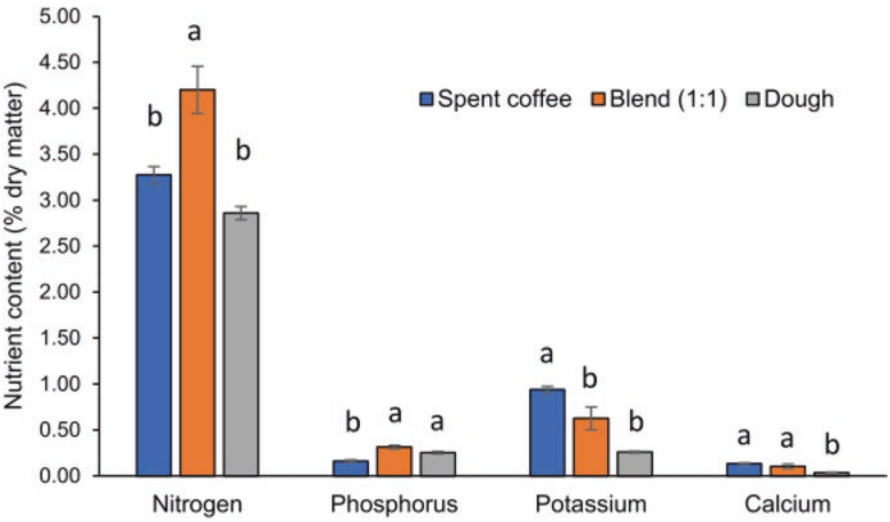

Fig. 6.26 Mean (±SE) nitrogen, phosphorus, potassium, and calcium (% dry matter) of frass from black soldier fly larvae when cultured with spent coffee, dough or an equal blend of these after 35 days. Different letters indicate significant differences ($p < 0.05$) [106]

content that could be used as nutrients for animal feed. The black soldier fly larvae can be consumed as food to humans, and animals to gain nutrients from the larvae. Higa et al. [146] mentioned that most Americans rejected to consume the black soldier fly larvae directly, and they preferred to consume indirect ways. Higa et al. [146] suggested that the indirect way of consumption was that the animals were fed by the black soldier fly larvae, the animals were consumed by humans, and this way was more acceptable.

6.6.3 Malaysia

Microwave-assisted extraction of black soldier fly larvae was prepared to extract the lipid from the black soldier fly larvae that fed in food waste. The optimum conditions of microwave-assisted extraction were determined to ensure that the lipid yield was the highest such as 260 W microwave power, 31 min extraction time, and 1:15 solid to solvent ratio (Table 6.19). The lipid yield from the microwave-assisted extraction method was enhanced by 20% without significantly affecting the lipid characteristics compared to the Soxhlet method. Thus, microwave-assisted extraction methods could produce high lipid yield and acceptable lipid stability to generate biodiesels [149]. Blended sewage sludge substrates could increase the reduction waste rate by using the black soldier fly larvae. The lipid yield was high because the black soldier fly larvae consumed the blended sewage sludge substrates, which were rich in protein and lipid. The process to convert the lipid from the larvae into biodiesel was the base-catalyzed transesterification process. The fatty acid methyl ester profile from the black soldier fly larvae had shown the presence of a significant amount of saturated and monosaturated fatty acids, thus black soldier fly larvae fed with the blended sludge sewage substrates could produce high-quality biodiesel [105]. Wong et al. [110] had applied the acid-catalyzed esterification followed by the base-catalyzed transesterification process to determine the mixture of fatty acid methyl esters from extracted black

Table 6.19 Experimental and predicted values of lipid content (%) obtained by Box–Behnken Design in Response surface methodology (RSM) [149]

Run	Microwave power (X_1)	Sample to solvent to (X_2)	Extraction time (X_3)	Lipid content, %	
				Observed	Predicted
1	230	10	30	22.46	22.73
2	290	10	30	20.65	21.87
3	230	20	30	26.35	25.13
4	290	20	30	19.97	19.70
5	230	15	20	20.76	20.97
6	290	15	20	19.91	19.17
7	230	15	40	23.72	24.46
8	290	15	40	20.17	19.96
9	260	10	20	20.89	20.41
10	260	20	20	21.01	22.02
11	260	10	40	25.07	24.06
12	260	20	40	22.18	22.66
13	260	15	30	30.23	30.39
14	260	15	30	30.53	30.39
15	260	15	30	30.36	30.39
16	260	15	30	29.96	30.39
17	260	15	30	30.89	30.39

Table 6.20 Effect of the different treatments on black soldier fly larvae meal [150]

Treatment of BSFL meal	Protein concentration of treated BSFL meal (μg/mL)	Protein concentration decreased (%)	*p*-value	
			μg/mL	%
T1	495.397 ± 2.741[d]	10.36 ± 0.84[b]	0.000	0.001
T2	534.500 ± 3.490[e,f]	3.29 ± 0.30[a]	0.000	0.001
T3	352.705 ± 6.091[c]	32.08 ± 1.92[c]	0.926	0.958
T4	361.167 ± 3.541[c]	30.46 ± 1.53[c]	0.926	0.958
T5	321.423 ± 1.175[b]	41.84 ± 0.37[d]	0.961	0.985
T6	280.782 ± 3.236[a]	49.20 ± 0.34[f]	0.906	0.960
T7	313.860 ± 6.867[b]	43.22 ± 0.98[d,e]	0.961	0.985, 0.078
T8	289.628 ± 3.880[a]	47.59 ± 0.79[e,f]	0.906	0.078, 0.960

Means with different superscript letters (a–f) within the same column differ significantly (Turkey test, $p < 0.05$), 10% NaCl (T1); 10% KCl (T2); 10% TAPzyme (T3); 20% TAPzyme (T4); 10% NaCl and 10% TAPzyme (T5); 10% NaCl and 20% TAPzyme (T6); 10% KCl and 10% TAPzyme (T7); and, 10% KCl and 20% TAPzyme (T8).

soldier fly larvae. The ex situ fermentation of 1.0% of *Rhizopus oligosporus* with coconut endosperm waste had produced high lipid yield and better biodiesel quality.

Protease is used to treat the black soldier fly larvae to allow the protein can be converted into amino acids, thus improving the absorption of nutrients. Zuki et al. [148] had utilized the Response Surface Methodology (RSM) to investigate the optimum conditions such as volume of water, the volume of protease, and time of incubation in achieving the highest decrease in protein content of black soldier fly larvae. Hybrid treatment had carried out to determine the potential of black soldier fly larvae meal protein hydrolysate as a sustainable alternative source of protein. Zuki et al. [150] demonstrated that the hybrid treatment with 10% potassium chloride (KCl) and 10% TAPzyme would have the lowest protein concentration of treated black soldier fly larvae meal and the highest decrease of protein concentration (Table 6.20). The combination of KCl and TAPzyme would cause the black soldier fly larvae protein to hydrolyze efficiently. The amount of TAPzyme in the hybrid treatment increased would slightly reduce the protein concentration, this synergistic effect had enhanced the growth, nutrient retention, and digestibility in animal feed production.

6.6.4 South Korea

Antimicrobial activity was carried out in the black soldier fly larvae to prevent the growth of bacteria in the larvae and enhance the growth of black soldier fly larvae. Lee et al. [151] demonstrated that *Lactobacillus* species can be used as antimicrobial peptides inducers in the black soldier fly larvae and the extract of *Lactobacillus casei* immunized black soldier fly larvae can restrict the growth of *Salmonella*

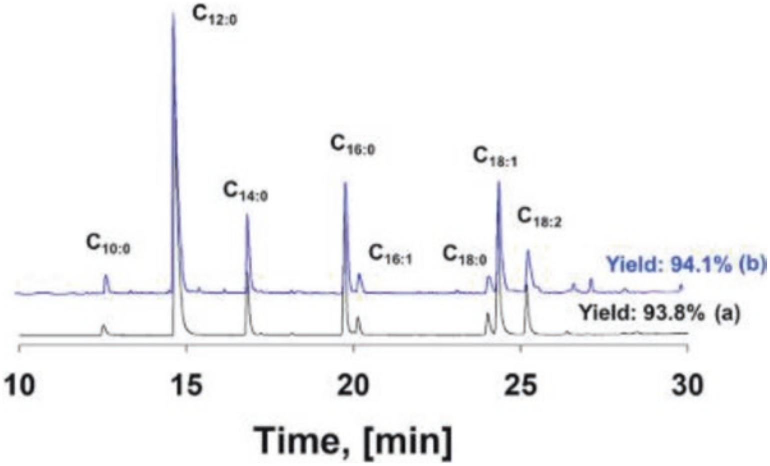

Fig. 6.27 Chromatogram profiles of fatty acid methyl esters (FAMEs) derived from base-catalyzed transesterification of BSFL extract at 65 °C for 8 h (*a*) and non-catalytic transesterification of BSFL extract at 390 °C for 1 min (*b*) [123]

species without developing the cytotoxicity in normal animals cells. Thus, the *L. casei* immunized black soldier fly larvae extract is an effective natural antibiotic.

Kim et al. [19] mentioned that the microwave-dried black soldier fly larvae meal was safe to use as animal feed ingredient because the contents of undesirable heavy metals in the black soldier fly larvae were not exceeded the maximum allowable limit. Jung et al. [123] had applied the non-catalytic transesterification and base-catalyzed transesterification to directly convert the black soldier fly into biodiesel. The fatty acid methyl ester of both transesterifications had compared, non-catalytic transesterification had generated high yield which was 94.1% (Fig. 6.27). Non-catalytic transesterification was recommended for biodiesel production because it did not produce alkaline solution and converted the methanol and lipid rapidly into biodiesel.

6.6.5 Italy

The lactic acid bacteria have the potential to generate antimicrobial metabolites. Saadoun et al. [152] demonstrated the fermentation of insect-derived biomasses in the puparium and adult insect at the end of the life cycle to find out the in vitro antimicrobial activity of fermented insects. Two bacterial strains such as *Lacticaseibacillus rhamnosus* 1473 and *Lactiplantibacillus plantarum* 285 were used for the fermentation and the antimicrobial activity of insect waste was examined toward three pathogenic strains such as *Salmonella enterica*, *Listeria monocytogenes*, and *Escherichia coli*. The puparium and adults are fermentable and showed

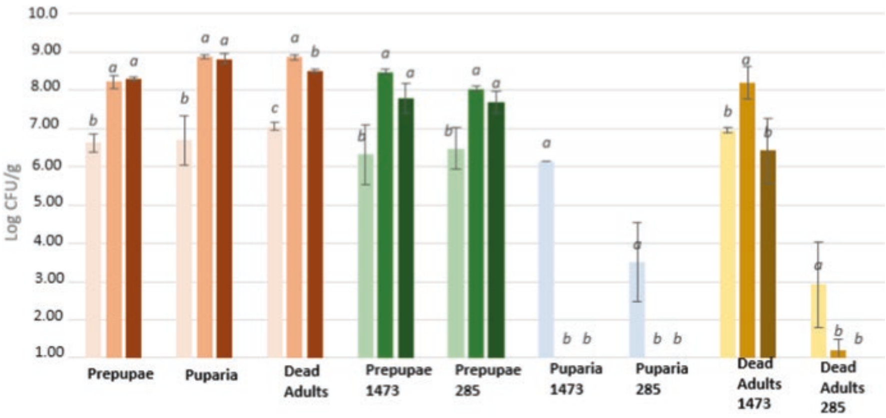

Fig. 6.28 Growth of *Listeria monocytogenes* LMG 21264 on fermented/unfermented insect waste after inoculum (first line/light color), 24 h (second line/medium color), and 48 h (third line/dark color). Starting inoculum 6 log CFU/g. Letters a–c mark significant ($p < 0.05$) differences among the samples. 1473: fermented with *L. rhamnosus*; 285: fermented with *L. plantarum* [152]

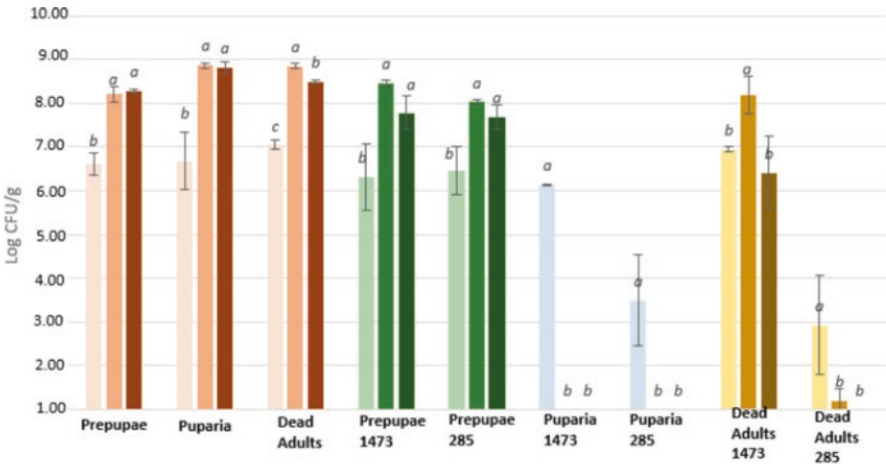

Fig. 6.29 Growth of *Salmonella Rissen* on fermented/unfermented insect waste after inoculum (first line/light color), 24 h (second line/medium color), and 48 h (third line/dark color). Starting inoculum 7 log CFU/g. Letters a–c mark significant ($p < 0.05$) differences among the samples. 1473: fermented with *L. rhamnosus*; 285: fermented with *L. plantarum* [152]

antimicrobial activity after fermentation. Figures 6.28, 6.29, and 6.30 represent the growth of the three pathogenic strains in the fermented and unfermented samples.

Insect meal is an alternative meal that can be replaced with the fishmeal due to its low carbon footprint and high nutritional value. Fronte et al. [153] indicated that the fishmeal can be replaced with the *H. illucens* meal as animal feed for zebrafish. There was no negative effect on the intestine histology of zebrafish such as

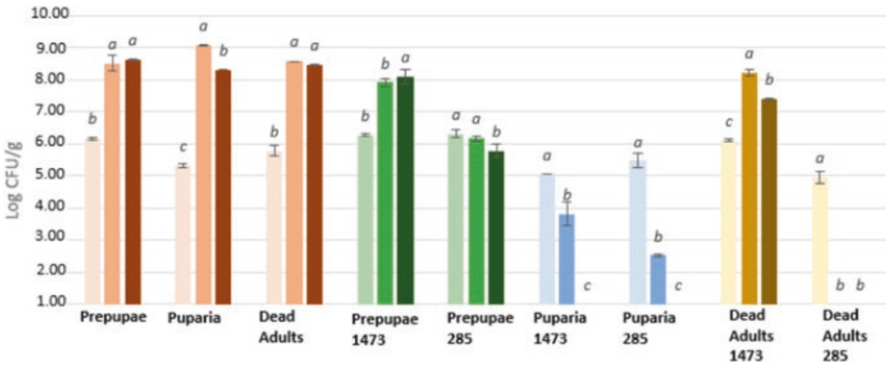

Fig. 6.30 Growth of *Escherichia coli* k88 on fermented/unfermented insect waste after inoculum (first line/light color), 24 h (second line/medium color), and 48 h (third line/dark color). Starting inoculum 7 log CFU/g. Letters a–c mark significant ($p < 0.05$) differences among the samples. 1473: fermented with *L. rhamnosus*; 285: fermented with *L. plantarum* [152]

Table 6.21 Survival rate and growth parameters of zebrafish fed with experimental diets (control, fifth instar, and prepupae) for 60 days [154]

Treatment	Control	5th instar	Prepupae
Survival rate (%)	92.50	93.75	96.25
Final total length (mm)	24.11	26.08	28.46
Height (mm)	5.38	5.71	6.11
Final body weight (mg)	132.99	159.41	189.70
Weight gain (mg)	127.99	154.41	184.70
Daily growth rate (mg/day)	2.13	2.57	3.08
Specific growth rate	5.37	5.67	5.97

mortality, feed intake, body weight gain, and feed conversion rate. However, the fishmeal replacement rate was increased would cause the enzyme activities to decrease. Lanes et al. [154] demonstrated that fishmeal can also be replaced with the defatted black soldier fly larvae and prepupae meal to enhance the growth of zebrafish. When the zebrafish were fed with the black soldier fly prepupae, they had the highest survival rate and better growth performance (Table 6.21).

Caimi et al. [155] demonstrated that partially defatted black soldier fly larva meal can be used as a suitable ingredient in low fishmeal-based diets for rainbow trout. There was no adverse effect on the growth performance, somatic indexes, fillet physical quality parameters, chemical composition, and diets digestibility. On the other hand, when the level of black soldier fly larva meal was increased, the fatty acid composition of fillet was reduced. Bruni et al. [156] stated that the skin of rainbow trout consists of n-3 long-chain polyunsaturated fatty acid which provides a high ability in human nutrition and health. The rainbow trout fed with 25% replacement of *H. illucens* had shown high DHA content, which is the role of DHA as an important nutrient for brain health and function.

6.7 Global Warming Potential

Global warming is a global issue that concern related to climate change. Waste management such as incineration, landfill activities, and composting will cause the emissions of greenhouse gases to the surrounding environment. The composting process will release carbon dioxide and methane into the atmosphere and may bring the effect of global warming if the toxic gases are emitted without any action taken. The global warming potential can be analyzed by the life cycle assessment. Table 6.22 shows the greenhouse gas emission produced from the black soldier fly larvae and the global warming potential.

Song et al. [127] revealed that the global warming potential of the black soldier fly larvae frass was lower than the incineration, where the fresh frass had the lowest emission. Further composting process of black soldier fly larvae frass would increase the global warming potential of black soldier fly larvae frass as more carbon would be disappeared in the form of biogenic carbon dioxide. The further composting in black soldier fly rearing chamber under natural conditions would have 52% high emission as the potential avoidance of using black soldier fly larvae as a fishmeal replacement could not be utilized. The global warming potential from the direct, indirect, and avoided emissions of black soldier fly treatment and further composting is shown in Fig. 6.31.

Mertenat et al. [162] demonstrated that composting had double the global warming potential of black soldier fly treatment facility and greenhouse gas emissions by the larvae feeding on the waste was lower compared to the microbial emissions in the open composting process. The direct emissions from the black soldier fly treatment facility were lower than from composting facility, where the black soldier fly treatment showed 72% of the overall related global warming potential while composting showed 98%. Mertenat et al. [162] also revealed that the indirect emissions were represented by the electricity consumption in the black soldier fly treatment, where black soldier fly required more electricity consumption during the rearing and harvesting phases. Therefore, black soldier fly biowaste treatment had very low direct greenhouse gas emissions and potentially high global warming potential

Table 6.22 Greenhouse gas emission and global warming potential

Substrates	CH_4	CO_2	Global warming potential—CO_2eq	References
Wheat bran and flour	58 mg	2750 g	17	[157]
Pig manure	10,066 mg	1956 g	344	[158]
Meat and bone meal	2.3226 g CO_2-eq/kg DM	481.63 g CO_2-eq/kg DM	–	[159]
Cattle manure	36.5 mgCH_4/kg	–	–	[160]
Swine manure	134.2 mgCH_4/kg	–	–	[160]
Pig manure and corncob	0.49 g/kg	151.68 g/kg	–	[161]

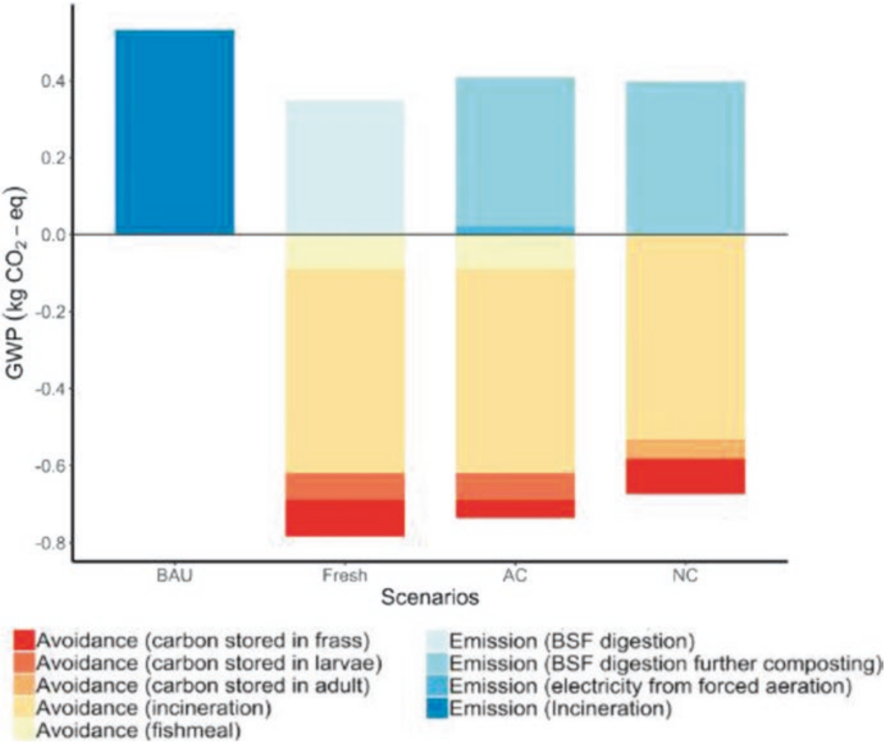

Fig. 6.31 Global warming potential per functional unit expressed in kg CO_2-eq from direct, indirect, and avoided emissions of black soldier fly treatment and further composting. BAU represents the incineration of food waste for electricity generation [127]

reduction. Figure 6.32 shows the global warming potential from direct, indirect, and avoided emissions of black soldier fly treatment and composting.

Parodi et al. [158] revealed that the global warming potential of the direct gaseous emissions during the black soldier fly larvae rearing with the pig manure was high. When the waste treated with the black soldier fly larvae, there was high emission of carbon dioxide due to the larval respiration that occurred during the feeding. The emission of methane was relatively high when the black soldier fly larvae were fed with the manure, the emission of methane could reduce due to the aeration caused by the larval movement through the crate when the larvae had grown larger and the reduction in the quantity of substrate present. When compared to Parodi et al. [157], the black soldier fly larvae fed with wheat bran and flour had relatively low global warming potential and methane gas emissions. However, the comparison of global warming potential and greenhouse gas emissions should be compared with other manures, and not compared with the food waste with the manures [158]. The food waste treated by the black soldier fly larvae could reduce the greenhouse gas emission and gain high biomass to produce bioavailable protein and lipid for animal feeding [159].

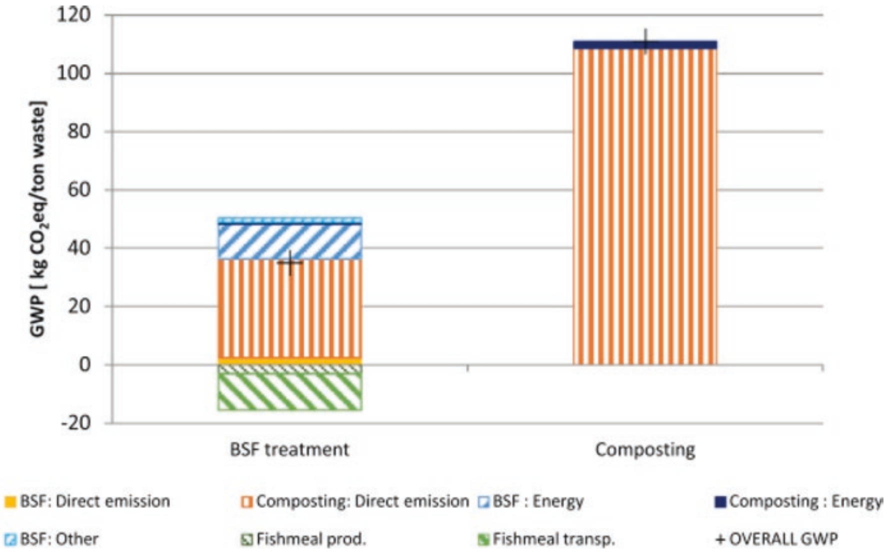

Fig. 6.32 Global warming potential per ton biowaste expressed in kg CO_2eq from direct, indirect, and avoided emissions of black soldier fly treatment and composting [162]

6.8 Challenge and Future Development

Black soldier fly larvae technology is the common application used for composting, animal feeds, fertilizer, and biodiesel production. This technology had been widely utilized in the agriculture fields and industrial activities because it is eco-friendly. However, several challenges are being faced when conducting the black soldier fly larvae technology such as conditions of rearing the black soldier fly, feeding substrates, and production of biomass in social, environmental, and economic aspects. Table 6.23 represents the benefits and challenges of applying the black soldier fly technology.

Black soldier fly technology has contributed many advantages to humans and animals. In developing countries, the black soldier fly larvae technology can help to decrease the burden of organic fertilizer shortage in the market and contribute a new income opportunity for a small-scale enterprise. The organic waste can be reduced with the help of black soldier fly larvae through the composting method. Black soldier fly larvae not only enhance the composting process but also minimize odor problems. The waste treated by the black soldier fly will not generate heavy fumes in the surrounding environment. Landfill and incineration are not recommended to treat organic waste. Landfill requires large land use and produces leachate; the leachate will infiltrate into the ground which results in the groundwater being polluted. Incineration consumes high temperature to treat the waste and will emit toxic gases, especially carbon dioxide to the surrounding environment result in air

Table 6.23 Benefits and challenges of black soldier fly technology

Benefits	Challenges/limitations
Larvae or prepupae as an alternative animal feed	Limited to organic waste
Lipid from larvae can generate biodiesel	Necessary to monitor the environmental conditions and breeding parameters
Waste residue as fertilizer	High global warming potential for further composting [127]
Enhance the composting process and minimize odor problems	High initial investment
Minimize environmental pollution	The economies of scale must be carefully studied to generate a sufficient number of larvae to replace or augment animal feed requirements
Reduce the organic waste	Egg sterilization and ensure the environment to store the egg is uncontaminated
Minimal land requirement	Technical feasibility is not broadly examined in developing countries

pollution. Therefore, composting by using the black soldier fly larvae is suitable to treat the organic waste due to low environmental pollution. However, high carbon dioxide is emitted in the process due to larval respiration.

The waste residue after decomposed by the black soldier fly larvae can be used as organic fertilizer. The frass fertilizer can be utilized in the agriculture field to enhance the growth of the plant and increase the yield of products. The use of frass can decrease reliance on inorganic fertilizer, the inorganic fertilizer will affect the ground quality, and the chemical from the fertilizer will infiltrate into the ground that causes groundwater pollution. The waste residue is not only used as fertilizer but also used as a soil amendment. The nitrogen content from the waste residue can enhance the soil quality and contribute to the growth of the plant. The black soldier fly larvae consume the nutrients from the substrates and store them in their bodies such as protein and fat. The protein in the black soldier fly larvae can be used as an alternative protein or animal feed. The soybean meal or fish meal can be replaced by the black soldier fly larvae meal, result in the animal has better growth. The lipid in the black soldier fly larvae can generate biodiesel or biofuel. The fat from the black soldier fly larvae produces a better quality of biodiesel and is safe to use compared to petroleum diesel.

On the other hand, black soldier fly technology has met many challenges and limitations. The rearing or breeding conditions of black soldier fly must be monitored time by time to ensure the conditions is optimum for the black soldier fly to carry out mating and other activities. The eggs of black soldier fly must be sterilized, and the environment to store the eggs should be clean and uncontaminated. The black soldier fly larvae can decompose the organic waste through the composting method. However, if the waste residue is further composting, high emission of toxic gases to the surrounding environment that raising the global warming potential of black soldier fly frass, where more carbon is lost in the form of biogenic carbon dioxide. Only organic waste can be decomposed by black soldier fly larvae, other wastes are not available. A high investment cost is due to setting up the breeding and feeding location with optimum conditions initially and high maintenance cost to maintain the conditions. Some of the developed countries do not widely focus on technical feasibility.

In future research, the economic and technical feasibility needs to be considered. The cost of producing matured compost must be reduced [69] [163]. Future composting would cause environmental pollution, thus the research to control the emission of toxic gases need to be studied. Further composting on frass microbial diversity and activity, and then the crop growth and yield affected by the microbial diversity and activity also need to be studied [127]. The bioaccumulation of heavy metals in the *H. illucens* larvae needs to be measured before being used as animal feed [120].

6.9 Conclusion

The solid waste generated from the global is increasing; as estimated, it will reach 3.40 billion tons by the year 2050. Those developing countries and low-income countries contribute huge amount of solid wastes, especially in India. China and India are the countries that produce more wastes due to large population. Organic waste is one of the wastes generated globally. it includes food waste and animal manure. The organic wastes are generated from the household and farm, proper waste management need to be carried out to prevent environmental pollution. Landfills, incineration, anaerobic digestion, and composting are the waste management that can be utilized to manage and reduce waste from the environment. However, recently, landfills are not recommended to use as waste management in many countries due to the requirement of large land use and methane gas production. Incineration can reduce large amount of wastes in a short period, but the process emits toxic gases to the surroundings such as carbon dioxide and causes air pollution. Landfill and incineration are still widely applied in China for waste management due to large amount of wastes generated every year. Composting is not broadly utilized in China because it is limited to organic waste; it is not suitable for wastes other than organic waste. On the other hand, India has widely applied the composting method to manage waste.

Composting is process in which the wastes undergo aerobic process under controlled condition. There are several types of composting methods such as aerated static pile composting, aerobic composting, windrow composting, vermicomposting, and in-vessel composting [164]. Co-composting can be practiced to produce a better quality of compost products that can be used in the agriculture field. Food waste can be composted together with other substrates to enhance the quality of the compost materials; other than food waste, animal manure, rice straw, and olive waste can be composted with other substrates as well. In this study, black soldier fly can be used for composting to decompose the organic waste. The condition to rear the black soldier fly must be in optimum condition, and the food that feeds the larvae must have sufficient nutrients, thus the black soldier fly larvae can grow well. Proteins and lipids are the nutrients that are essential for the growth of black soldier fly, and the nutrient of substrates can be improved by mixing with other substrates or undergoing fermentation process, thus the black soldier fly larvae have better growth performance. The black soldier fly can convert the waste into biomass, such as animal feed, frass fertilizer, and biodiesel production. Many countries have utilized black soldier fly technology in industrial and agriculture areas.

Black soldier fly technology brings many benefits to humans and animals; however, there are still have some challenges meet when conducting the black soldier fly technology. Black soldier fly larvae treatment technology has fewer effects in terms of greenhouse gas emissions and land requirement; however, some of the studies revealed that the black soldier fly technology had higher environmental effects in terms of transportation, electricity consumption during composting and feed production, and energy consumption for bioconversion processes. Thus, the black soldier fly technology has a higher global warming potential when compared with other conventional processing methods. The problems can be overcome by conducting iterative research on black soldier fly technology to identify the gaps and enhance the knowledge resource networks to have the better technical refinement of layout and operational facility to improve the profitability. In future research, technical feasibility and scaling up black soldier fly larvae technology must be focused on in developing countries, and the cost of production must be reduced.

Glossary

Adsorbable organic halides (AOX) A measure of the organic halogen load at a sampling site.

American Society of Mechanical Engineers (ASME) American professional association that promotes the art, science, and practice of multidisciplinary engineering and allied sciences around the word.

Anaerobic digestion A process through which bacteria break down organic matter in the absence of oxygen.

Animal feed Food given to domestic animals, especially livestock.

Animal manure Organic matter that is used as organic fertilizer in agriculture, especially consists of animal feces.

Antibiotic resistance Bacteria develop the ability to survive exposure to antibiotics designed to kill them or stop their growth.

Avian infectious bronchitis An acute and highly contagious respiratory disease of chickens.

Biochars Charcoal that is produced by pyrolysis of biomass in the absence of oxygen.

Biodiesel A form of diesel fuel derived from plants or animals and consisting of long-chain fatty acid esters.

Biological oxygen demand (BOD) The amount of oxygen consumed by bacteria and other microorganisms while they decompose organic matter under aerobic conditions at a specified temperature.

Biomolecules The ions or molecules present in living organisms.

Cation-π EDA interactions Non-covalent molecular interaction between the face of an electron-rich π system and an adjacent cations.

Cetane number An indicator of the ignitibility of diesel fuels.

Chemical oxygen demand (COD) The amount of dissolved oxygen that must be present in water to oxidize chemical organic materials.

Co-composting A process of the aerobic degradation of organic compounds using more than one feedstock.

Composting Aerobic biological decomposition of organic waste under controlled conditions.

Cost–benefit analysis (CBA) Systematic process that businesses use to analyze which decisions to make.

Docosahexaenoic acid (DHA) An omega-3 fatty acid that is primary structural component of the human brain. Cerebral cortex, skin, and retina.

Environmental impact assessment (EIA) Process of examining the anticipated environmental effects of a proposed project from consideration of environmental aspects at the design stage.

Ex situ fermentation Organic substrates that are fermented at first by microorganisms before used.

Fatty acid methyl esters (FAMEs) Type of fatty acid ester that are derived by transesterification of fats with methanol.

Fenton-like process The reactions of peroxides with iron ions to form active oxygen moieties that oxidize the target compounds.

Food waste Any food or inedible components of food that have been removed from the food supply chain and maybe retrieved.

Germination index A measure of the percentage and speed of germination.

Global warming potential (GWP) The heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of carbon dioxide.

Greenhouse gas emission Greenhouse gases vented to the Earth's atmosphere because of humans.

Incineration A process of controlled and complete combustion of solid waste in an oxidizing atmosphere.

Inductively coupled plasma-optical emission spectroscopy (ICP-OES) analysis A trace level, elemental analysis technique that uses the emission spectra of a sample to identify, and quantify the elements present.

In situ fermentation The microorganisms are added to implement the fermentation process simultaneously with the valorization of organic substrates.

Life cycle assessment (LCA) Methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service.

Material flow analysis An analytic method to quantify flows and stocks of materials in a system.
Microbial fermentation The process that enhances the nutritional composition of substrates through microbial modification.
Microwave-assisted extraction A technique based on the use of microwave energy to help the transfer of the solutes from the matrix into the solvent.
Organic waste Any material that is biodegradable and comes from either a plant or an animal.
Oviposition Expulsion of the egg from the oviduct to the external environment.
Response surface methodology (RSM) A technique to optimize the response when two or more quantitative factors are involved.
Sanitary landfill An engineered facility and managed to minimize public health and environmental effects while disposing of municipal solid waste.
Technical feasibility The process of proving that the concept is technically possible.
Transesterification Reversible reaction and carried out by mixing the reactants such as fatty acids, alcohol, and catalyst.
US Environmental Protection Agency (USEPA) The United States Federal Government Agency whose mission is to protect human and environmental health.
Volatile organic compound (VOC) Compounds that have a high vapor pressure and low water solubility.

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Chapter 7
Biodrying of Municipal Solid Waste: A Case Study in Malaysia

Nurul'Ain Ab Jalil, Irfana Kabir Ahmad, Hassan Basri, Noor Ezlin Ahmad Basri, Hamidi Abdul Aziz, Lawrence K. Wang, and Yung-Tse Hung

Abstract Municipal solid waste (MSW) in Malaysia contains excessive moisture, which complicates recycling segregation and makes the use of advanced technology, such as solid waste combustion, inappropriate and harmful. Furthermore, MSW pre-treatment to reduce moisture content is uncommon in Malaysia. Biodrying is a cost-effective and environmentally beneficial technology since the fundamental principle relies on internal energy generated by the decomposition of organic waste. The process of biodrying could be a useful alternative for MSW management, allowing for the production of derived fuel. This chapter focuses on the potential of biodrying to reduce

N. A. Jalil (✉)
Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan, Malaysia
e-mail: nurulain@ukm.edu.my

I. K. Ahmad · H. Basri · N. E. A. Basri
Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan, Malaysia
e-mail: irfana@ukm.edu.my; drhb@ukm.my; noorezlin@ukm.edu.my

H. A. Aziz
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Solid Waste Management Cluster, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: cehamidi@usm.my

L. K. Wang
Lenox Institute of Water Technology, Latham, NY, USA

Y.-T. Hung
Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, OH, USA
e-mail: y.hung@csuohio.edu

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excessive moisture content for MSW, particularly in Malaysia. Through nine sub-chapters, this book chapter provides an overview of the fundamentals of solid waste biodrying as well as the potential of solid waste biodrying systems in Malaysia. The first chapter provides a succinct overview of the concerns and challenges of solid waste management in the world and Malaysia. In Chap. 2, a concise explanation of the drying technology is described. The solid waste biodrying treatment system is covered in Chap. 3, followed by the design of the biodrying reactor in Chap. 4. In Chap. 4, there is also a more detailed description of the case study that is being conducted at Universiti Kebangsaan Malaysia. The factors that influence the biodrying process are discussed in Chap. 5. Chapter 6 presents the direct observation of fieldwork at solid waste biodrying plants in Malaysia and abroad. The importance of biodrying from various perspectives is elaborated in Chap. 7, and the potential use of solid waste biodrying in solid waste management in Malaysia is discussed in Chap. 8. Finally, Chap. 9 concludes the importance of a solid waste biodrying system in the future.

Keywords Municipal solid waste · Biodrying · Excessive moisture · Renewable energy · Moisture content · Temperature · Ventilation periods

Nomenclature

ASTM	American Society for Testing and Materials
EEB	European Environmental Bureau
GDP	Gross domestic product
MHLG	Ministry of Housing and Local Government
MSW	Municipal solid waste
MYR	Malaysian Ringgit
NSP	National Strategic Plan
NSWMD	National Solid Waste Management Department
PU	Polyurethane
PVC	Polyvinyl chloride
RDF	Refuse derived fuel
SMSW	Synthetic municipal solid waste
SWCorp	Solid Waste Corporation
TNB	Tenaga Nasional Berhad
UKM	Universiti Kebangsaan Malaysia
WtE	Waste to energy

7.1 Introduction

7.1.1 Overview Global Solid Waste Management

In any civilisation, solid waste management is a necessary service. Solid waste encompasses to a wide range of waste materials thrown as undesired and worthless as a result of animal and human activity. Every year, 7–9 billion tonnes of waste are produced worldwide [1]. In 2016, the worlds' cities generated 2.01 billion tonnes of solid waste, amounting to a footprint of 0.74 kg per person per day but ranging widely from 0.11 to 4.54 kg. Annual waste generation is expected to increase by 70% rapid increase in population and urbanisation from 2016 levels to 3.40 billion tonnes in 2050 [2]. The World Banks's: What a Waste 2.0 report estimates that rapid urbanisation, population growth and economic development will push global waste to increase by 70% throughout the next three decades. As well as looking at global trends, What a Waste 2.0 examines how waste is managed regionally. Currently, East Asia and Pacific region is the highest region that generates 23% of the world's waste, followed by Europe and Central Asia with 20% of waste generated, as shown in Fig. 7.1. Despite having only 16% of the world's population, high-income countries collectively generate over one-third (34%) of the world's garbage (Fig. 7.2). Only 5% of the world's waste is produced by 9% of the world's population who live in low-income countries. Table 7.1 shows that average waste generation varies significantly among countries, ranging from 0.11 kg per capita per day to 4.54 kg per capita per day.

In the municipal solid waste stream, waste is categorised as food and green, paper and cardboard, plastic, glass, metals, rubber, wood and 'other'. Waste composition refers to the classification of different types of materials in municipal solid waste. A typical waste audit is used to determine waste composition. Samples of waste are collected from generators or final disposal sites, categorised into specified categories, and weighed. These categories can be refined further, however for basic solid waste planning purposes, these eight are probably preferable. The composition of MSW on a global scale is seen in Fig. 7.3, with food and green waste accounting for 44% of global waste. Another 38% of waste was comprised of dry recyclables, which is plastic, paper and cardboard, metal, and glass.

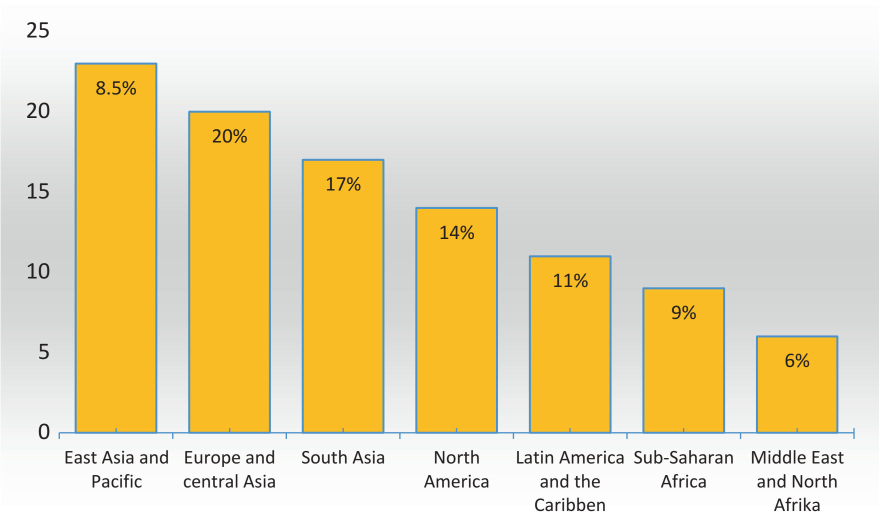
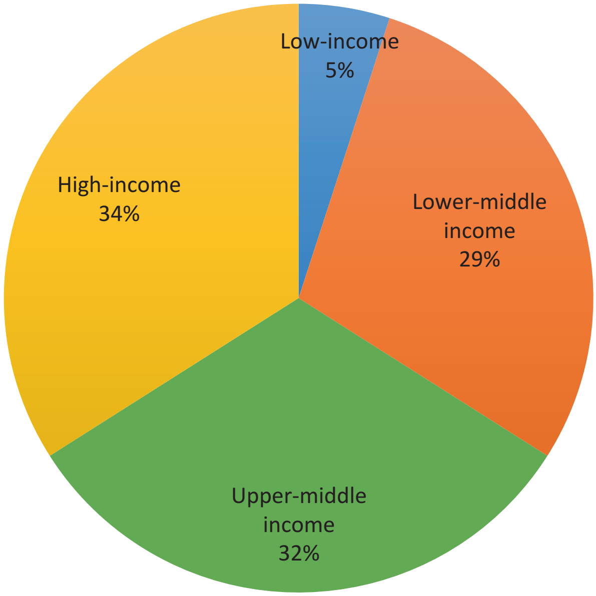


Fig. 7.1 Waste generation by region [2]

Fig. 7.2 Waste generation by income level [2]



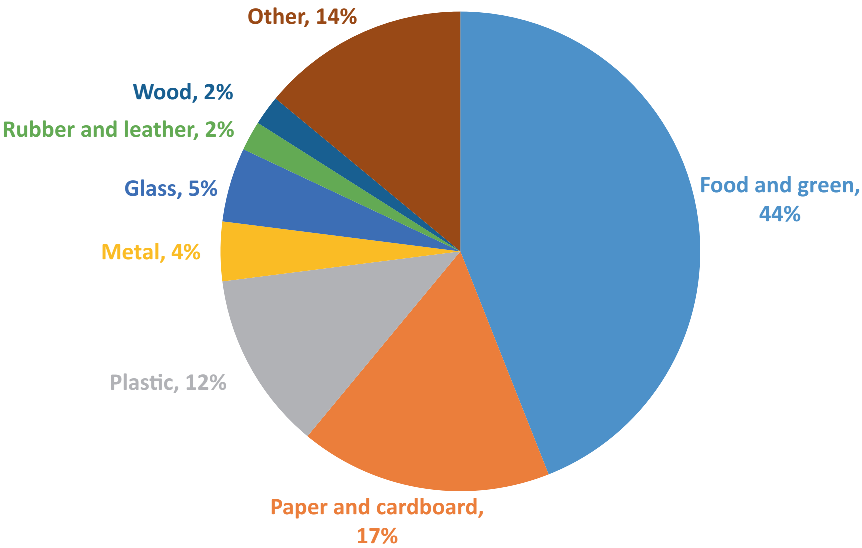


Fig. 7.3 Global waste composition [2]

Table 7.1 Ranges of average national waste generation by region [2]

No	Region	Average waste generation kg/capita/day
1	Sub-Saharan Africa	0.48
2	East Asia and Pacific	0.56
3	South Asia	0.52
4	Middle East and North Africa	0.81
5	Latin America and the Caribbean	0.99
6	Europe and Central Asia	1.18
7	North America	2.21

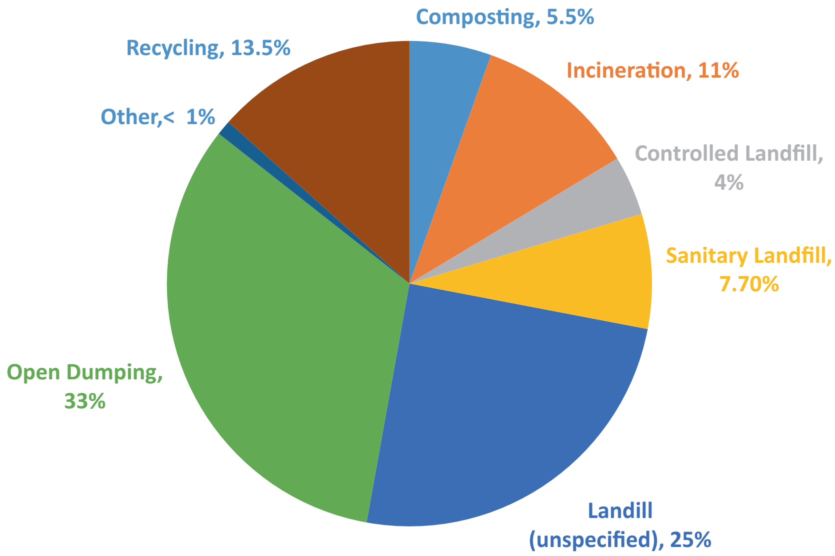


Fig. 7.4 Global waste treatment and disposal [2]

According to What a Waste 2.0, nearly 40% of waste is disposed of in landfills around the world. A total of 19% of MSW is recovered through recycling and composting, while 11% is incinerated using current technology. Governments are progressively recognising the risks and costs of dumpsites and seeking sustainable waste disposal techniques, regardless of the fact that 33% of waste is still dumped openly globally. Figure 7.4 depicts the global treatment and disposal of waste.

7.1.2 *Solid Waste Management in Malaysia*

Malaysia is a tropical country in Southeast Asia's central region, with a total landmass of 329,847 km^2 (Fig. 7.5). It is located between the longitudes of 100° and 120° east and the Equator and 7° north latitudes. The South China Sea separates

Malaysia into two regions: West Malaysia and East Malaysia. The Peninsular of West Malaysia is comprised of 11 states. East Malaysia is comprised of the two states of Sabah and Sarawak; both are located on Borneo's island. Kuala Lumpur is the capital, and Putrajaya is the federal government's seat. Malaysia is bordered by several countries. Thailand lies to Malaysia as a multi-ethnic, multi-cultural, and multi-lingual society. On the other hand, Bumiputera grew by 0.3% points to reach 69.5% in 2020 from 69.5% in 2019, with a population of 29.7 million. However, the Chinese and Indians population declined to 22.6% (2019: 22.8%) and 6.9% (2019: 6.8%), while others remained at 1.0%. Malaysia's population is expected to reach 32.7 million in 2020, up from 32.5 million in 2019, with an annual growth rate of 0.4%. The decline of population growth rate is attributed to the decrease in the number of non-citizens from 3.1 million (2019) to 3.0 million (2020) north of Malaysia, Singapore, and Indonesia are to the south, and the Philippines Islands are to the east.

The Ministry of Housing and Local Government (MHLG) in Malaysia is responsible for managing MSW with the participation of the private sector. Previously, MSW management in Malaysia was delegated to local authorities, as stated in Section 72 of the Local Government Act 1976. The local government is required by this act to provide public cleansing services, collection and waste disposal in a sanitary manner, either directly or through contract. Local governments, on the other hand, have had a number of issues with collection and transportation. On average, they spent 50% of the local authority's operating budget on MSW, with more than 50% spent on waste collection. As a result, the government has established a new solid waste management structure under the MHLG, known as the National Solid Waste Management Department (NSWMD), as the regulatory body and the Solid Waste and Public Cleansing Management Corporation to carry out operations. As indicated in Fig. 7.6, Malaysia's National Strategic Plan for Solid Waste Management (NSP 2005) proposed an integrated MSW management strategy that prioritised

Fig. 7.5 Map of Peninsular and East Malaysia (http://en.wikipedia.org/wiki/Malaysia) [3]

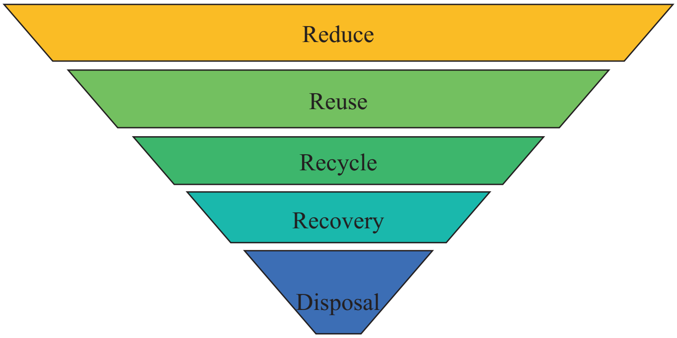


Fig. 7.6 Solid waste method hierarchy

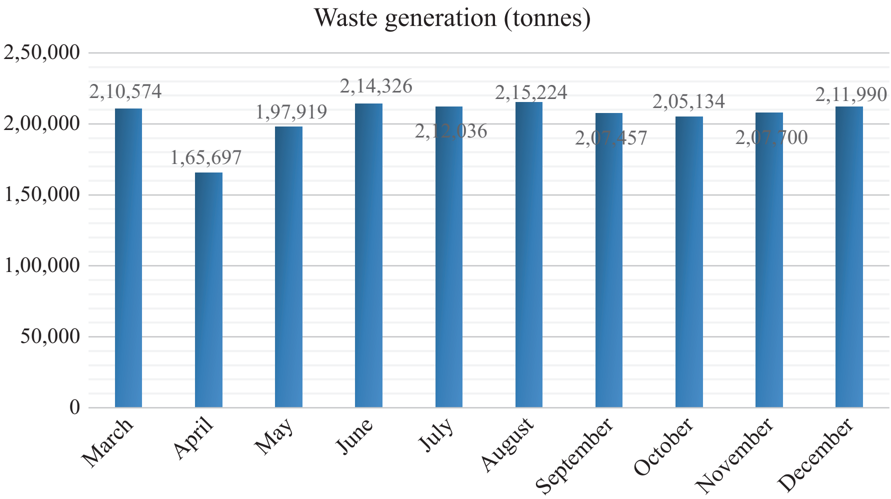


Fig. 7.7 Malaysians household waste in March–December 2020 [4]

reduction, reuse and recycle (3R), followed by recovery or treatment and finally disposal solutions. However, waste disposal in landfills remains the most common practise in the country.

7.1.2.1 Solid Waste Generation and Characteristic

In Malaysia, household waste generation has been gradually increasing in tandem with population and gross domestic product (GDP), as illustrated in Fig. 7.7, which play a crucial role in MSW generation. The increase of the population is parallel to the increasing GDP)is shown in Fig. 7.8. One of the primary issues in solid waste management in Malaysia is the high moisture content of solid waste. The moisture content of solid waste created in developed countries, where MSW is

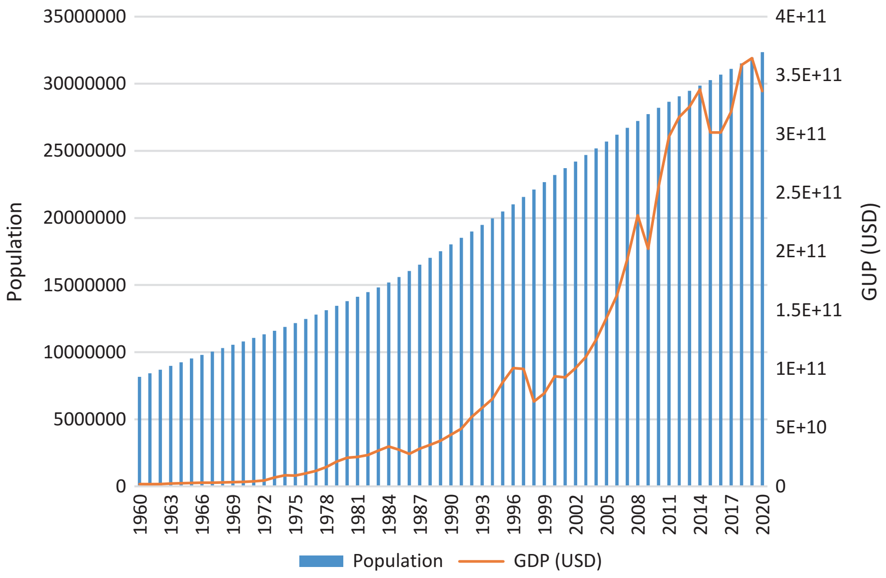


Fig. 7.8 Malaysian population and GDP)from year 1960 to 2020 [5]

Table 7.2 Characteristics of Kuala Lumpur MSW [14]

Proximate analysis (wet)	Weight (%)
Moisture content	55.01
Volatile matter content	31.36
Fixed carbon content	4.37
Ash content	9.26
Other parameter	
Bulk density (kg/m^3)	240
Net calorific value (kcal/kg)	2180

source-separated and collected systematically, is far lower than in developing countries, such as Malaysia, where MSW is dumped and collected 'as is' [6–11]. According to government statistics [12], the average amount of organic waste in high-income areas such as Petaling Jaya and Kuala Lumpur is around 48.32%. Paper comes in second with 23.56%, followed by plastic and rubber (9.37%), metal (5.93%), wood (4.82%), glass and ceramics (4.03%) and textiles (3.97%) as illustrations in Fig. 7.9. As seen in Table 7.2, Malaysian MSW contains a high concentration of food waste and organic garbage, resulting in high moisture content and bulk density of more than 200 kg/m^3. It is due to the variety of meals available in Malaysia, which are influenced by the country's diverse races and cultures. Furthermore, traditional Malaysian meals are made with coconut cream and curry is considered a wet food.

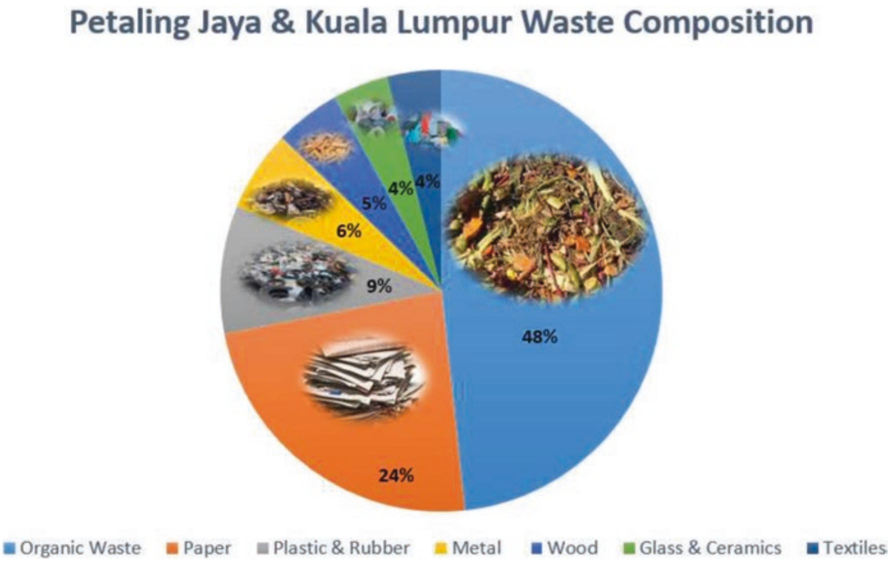


Fig. 7.9 Waste composition in Petaling Jaya and Kuala Lumpur [13]

Due to the high moisture content of the organic waste and food waste, landfilling is an ineffective method of solid waste disposal, as the extra moisture can contaminate nearby rivers and soils. Furthermore, research shows that organic waste decomposition anaerobic in landfills releases methane gas [14, 15]. Additionally, moisture in solid waste complicates the recycling process and reduces the calorific value when solid waste is employed as a fuel source. As a result, different treatments or approaches are required to tackle solid waste moisture content issues. The use of landfills brings with it plenty of issues that do biological solid waste treatment practice.

7.1.2.2 Recycling Rate

Recycling has gained widespread acceptance as a sustainable solid waste management approach due to its ability to lower disposal and waste transport costs while also extending landfill site life spans. Encouragement of the public to practice 3R is a solution to decrease waste disposal, mainly in landfills. This approach necessitates a huge commitment from the community or society to participate in solid waste management activities. The national recycling rate in 2002 was 5%, as presented in Table 7.3, and the Malaysian government has established a goal of increasing the recycling rate by 1% per year, with the goal of reaching a recycling rate of 22% by 2020. However, in 2018 the national recycling rate has reached 24.6%, as indicated in Fig. 7.10. In comparison to other developed countries, this achievement is extremely low. In 2019, Malaysia's recycling rate exceeded the target of 28.1%.

Table 7.3 Percentage of solid waste method in Malaysia [16]

Treatment	Rate percentage (%)		
	2002	2006	2020 (Target)
Recycling	5	5.5	22
Composting	0	1	8
Incineration	0	0	16.8
Inert landfill	0	3.2	9.1
Sanitary landfill	5	30.9	44.1
Other disposal site	90	59.4	0
Total	100	100	100

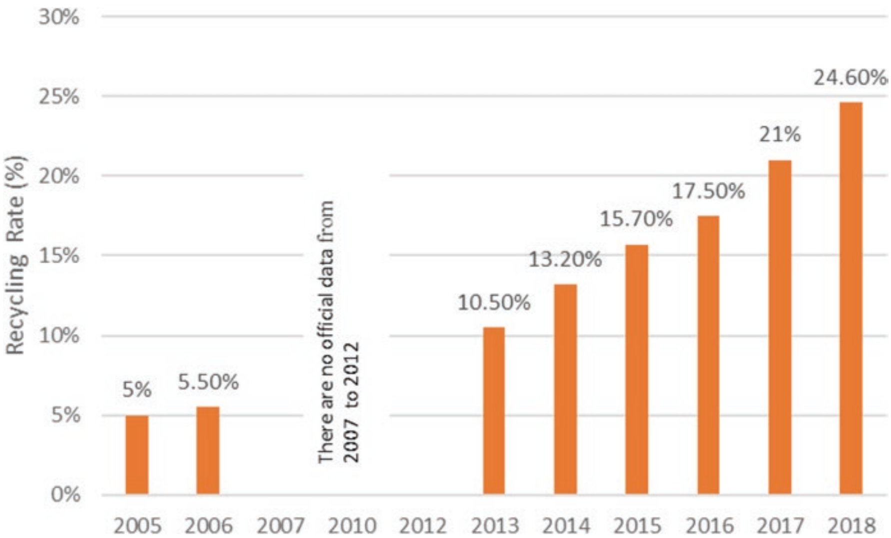


Fig. 7.10 Malaysia recycling rate [13]

This rate increased by 3.5% points from 24.6% in 2018 as a result of the government's initiative to separate solid waste from the source. South Korea and Singapore had the highest recycling rates in Asia, at 53.7% and 34.0%, respectively [17]. By 2020, the national recycling rate will have increased to 30.67% [15].

A new Eunomia report collaborated with the European Environmental Bureau (EEB) analyses a new analysis that examines recycling statistics from around the world to determine which countries really lead the municipal waste recycling league. This report reveals Germany has the highest recycling rate of any country in the world at 54%. Along with Germany, Taiwan, Wales, South Korea, and Belgium make up the top five countries that recycle the most. One of the reasons for Malaysia's low recycling rate is a lack of public response and participation. On the other hand, lack of market for recyclable, diminished public confidence due to poor collection services, lack of public awareness and promotion programme, lack of stakeholder participation, lack of local authority personnel dedicated to the programme and lack of policy and master plan focusing on recycling all contribute to Malaysia's recycling limitations [15].

7.1.2.3 Composting

Composting is the biological degradation of organic substrates by mesophilic and thermophilic microorganisms, which produces a stable end product that may be stored and applied to land without causing environmental harm [18]. Various ways and methods are used, such as typical composting piles or open methods, mechanical, vermicomposting and thermophilic composting. The black soldier fly method, which is a very efficient and productive technique, is currently being promoted to the public and entrepreneurs in Malaysia. In order to reduce the percentage composition of food waste in landfills, Solid waste Corporation (SWCorp) has taken several initiatives to promote food waste recycling using the latest food waste treatment technology. For example, in Malaysia, there are several facilities for recycling food waste that is often used, such as composting machines and anaerobic digesters, as shown in Fig. 7.11.

Fig. 7.11 Composting facilities in Malaysia [13]

Table 7.4 Total landfill and daily disposal rate of a landfill in Peninsular Malaysia, Sabah, Sarawak, WP Labuan, Malaysia [19]

No	Location	Sanitary landfill (LF)		Non-sanitary landfill (FL)		Total landfill
		No. of LF	Waste disposal (tonnes/day)	No. of LF	Waste disposal (tonnes/day)	
1	Peninsular Malaysia	20	14,405	68	14,424	88
2	Sabah, Sarawak, WP Labuan	4	1107	65	4607.23	69
3	Malaysia	24	15,512	133	19,031.23	157

7.1.2.4 Incinerator

Waste incinerators have been operated on a small scale in Malaysia, with only a few of them capable of recovering energy. Small-scale facilities were first installed in popular Malaysian tourist islands such as Langkawi, Cemeron Highlands, Pangkor and Tioman, where local authorities were in charge of collecting, transporting and incinerating waste [16]. However, because of the high cost of operation due to the high moisture content of the waste, which increased fuel costs and low technical ability, the usage of these incinerators has been discontinued recently. Due to this, it has become more difficult to find an incinerator technology that incinerates trash with high moisture content while also operating at a low cost.

7.1.2.5 Landfill

There are a few common types of disposal methods applied in Malaysia MSW management. In Malaysia, the landfill method of solid waste disposal is dominant [16], although many alternatives have been explored. Nowadays, landfilling is facing more difficulties because most landfills are approaching their threshold or have already exceeded their maximum capacity. Because of land scarcity and the proliferation of land values, the construction of new landfill sites has become more difficult [2]. The value of land near the landfill, on the other hand, will decrease. Table 7.4 reports the daily amount of MSW disposed of in sanitary and non-sanitary landfills in 2019 in Malaysia.

7.2 Drying Technologies

Drying is an operational unit found in most industrial sectors, whether small, medium or heavy industries. Among the reasons why the drying method is an incentive in the industry, apart from the energy-saving factor, is because it can conserve non-renewable resources, able to reduce carbon footprint and also control the effects of climate change [20]. In particular, in the field of solid waste management, planning for the selection of drying methods or technologies is crucial before the solid waste is sent for subsequent processes such as incineration [21]. There are various drying methods that are growing rapidly, including natural methods such as sun drying, convection drying and conduction drying.

Convection drying or also known as direct drying is where the heat is transferred directly between the material to be dried to the heater to increase the temperature and remove moisture from the material. The water vapour from the surface of the material moves away from the heater airflow. The speed of heat and water vapour transfer depends on the air velocity used, temperature and the size of materials to be dried [20].

Conductive drying is also referred to as indirect drying. This drying machine is where the material to be dried is not directly in contact with the heating medium. The heat transfer is through a heating medium that has a heating source such as fuel [20]. This method is used mainly for food and pharmaceutical products that must not be contaminated. Among the examples of technologies that apply this method of drying is the rotary dryer.

7.2.1 Solar Drying

Solar drying technology can be considered as a continuation of sun drying, and this method is more effective as it uses solar energy. Solar drying is a method that converts solar energy to thermal or heat energy so that it is able to dry without using fossil fuels [22]. Solar energy-based drying technologies in solar dryers make use of the greenhouse effect produced inside a structure covered with a sunlight-transmitting material [23]. This method is one of the alternatives to utilising renewable energy, where it reduces the dependence on electricity and fuel consumption. Malaysia's location, which is close to the equator, has caused the country to experience tropical weather that has the advantage of getting plenty of sunlight. Therefore, using solar energy in the drying industry is very suitable to be developed more productively.

The difference between solar drying technology and sun drying is that solar technology does not depend only on sunlight because the drying system is able to maintain a higher temperature compared to the temperature outside the system. In addition, an advantage of this technology's design is that it can protect the materials from being dried from rainy weather and animal disturbances. From the working principle aspect, solar technology can be divided into two systems which are passive systems and hybrid systems [24]. A passive system makes full use of sunlight and wind speed without the use of external energy, whereas the hybrid system needs additional external energy sources such as electricity and fuel [24].

7.2.2 Rotary Dryer

Rotary dryer technology is one of the drying methods that is used in the solid waste management industry. The rotary dryer is cylindrical in the shape of a rotating drum where the material to be dried is placed in the drum. In terms of the mechanism, the drying process occurs through the water evaporation process caused by the difference in water vapour pressure between the air and the material to be dried [25]. The drum rotates continuously, and at the same time, the heat of the heater is applied with a typical temperature of 200 °C–500 °C; however, the temperature can be increased to between 600 °C and 1000 °C [25]. This technology is used widely in most industries because failure is rare. However, nowadays, this technology is increasingly gaining competition from other drying technologies that are more effective and environmentally friendly. This is due to the decreasing rate of non-renewable resources, which is alarming and the sharp rise in fuel and natural gas prices.

7.2.3 Spray Drying

Spray drying technology is widely used especially in the food industry. The end result of the material dried by this method is in the form of powder or fine grains based on the physical and chemical properties of the material to be dried, the design and operation of the dryer. The operation and design of the dryer depend on the drying characteristics of the product and the desired powder specifications [26]. Among the important factors in the design of this spray dryer is the cyclone-shaped drying chamber which requires the selection of suitable materials, dimensions and surface characteristics of the cyclone wall so that the drying process can take place perfectly [27]. Among the advantages of this technology is the drying capacity that can be increased, and the drying process can take place in a short time [28]. This method is also suitable for non-heat-resistant materials such as food. However, this technology requires high costs and is only suitable to be used for liquid products with a certain degree of viscosity.

7.2.4 Freeze Drying

Freeze drying is one of the drying methods that has the advantage of maintaining the quality of dried products, especially for products that are sensitive to heat. This technology uses a conductive or indirect drying technique where the material to be dried is confined by the wall as a heating medium until the water content is evaporated. This drying technology mechanism requires that the materials that are to be dried be frozen first and then subjected to low pressure until the water content becomes ice and will directly evaporate [29]. Using a freeze dryer is better than an oven dryer because the water production rate is higher [30]. The duration of the freeze-drying process is between 18 and 24 h. The freeze-dried products are also more stable compared to spray-dried products [30]. This technology is widely used by the food and pharmaceutical industries. However, the costs of freeze-drying technology are very high.

7.3 Solid Waste Biodrying

Solid waste drying is a method that needs to be emphasised in the solid waste management system, especially for countries with high solid waste moisture content. The purpose of solid waste drying is to reduce the volume, stabilise and increase the heat value of the waste [31]. This relatively innovative method of recovery in Malaysia has been the focus in European countries over the last few decades when biological, mechanical treatment technology was first introduced there [32–35]. The solid waste biodrying method is widely developed industrially, especially in Germany and Italy, due to the increase of waste industry to energy which requires a high calorific value in the generation of energy [34]. In the solid waste management hierarchy, biodrying falls into the category of recovery or intermediate, where it involves the decomposition of organic matter that can convert the waste into disposable materials.

Among the scientists who are active in the evaluation and monitoring of solid waste biodrying method come from Italy, namely Adani et al. [36]; Rada et al. [37]; Sugni et al. [38]; Tambone et al. [39] who conducted observations of temperature and airflow parameters, China namely Cai et al. [40]; Zhang et al. [41] who are related to the working principles and the influence of parameters, Romania namely Negoi et al. [42] who is involved in the capability of the biodrying method in that country, Poland namely Dominczyk et al. 2014; Zawadzka et al. 2009 [43] who conducted biodrying on the organic waste.

In the context of drying, this method has already been widely explored, especially in the field of nutrition, agriculture, pharmaceuticals, pulp and paper and other industries [20]. The drying method in the industrial sector is very significant and is needed, especially to maintain the shelf life of the product produced. In the field of waste engineering, drying methods are used a lot, especially in the field of wastewater treatment [40, 44, 45]. To date, the majority of drying technology used in Malaysia uses conventional or external thermal energy that depends on oil and gas fuels such as the rotary dryer. Although these rotary dryers are well known for their usage in the drying industry, since the onset of the volatile fuel market crisis, many parties have begun to switch to more energy-efficient, environmentally friendly and cost-effective drying methods [46].

The solid waste biodrying method is a solid waste drying treatment that has the potential to be combined with technologies in solid waste management in Malaysia. This is due to the characterisation factor of solid waste in Malaysia, which has a very high moisture content, which is the source of constraints and weaknesses of high technology applications such as thermal treatment and RDF plant to operate properly and successfully. Drying solid wastes before incineration is able to improve the perfection of the combustion reaction, and this can indirectly reduce the release impact of harmful gases into the environment. The imperfect combustion reaction happens when the wastes contain too much water, causing a low combustion chamber temperature. Furthermore, some of the heat energy is also used as a water evaporation method [31].

7.3.1 Biodrying Definition

In general, drying means reducing the moisture content of materials using heat, causing the water to be evaporated into the air phase, which is to become vapour resulting in a dry output [47]. The term biodrying comes from two combined words, which are bio and drying. The combination of these two words indicates that the biodrying method involves a combination of biological and mechanical methods. In general, biological methods are methods that have a connection with organisms or living things. Therefore, the solid waste biodrying method can only occur when there is organic waste in the municipal solid waste to be used. In contrast, the scientific language for drying is hydration. This method occurs when a material to be dried suffers a total or partial loss of the water contained in it. Evaporation occurs when water in a material evaporates; that is, heat is given to the material.

Over the past decades, the biodrying industry has grown rapidly in the wake of worldwide demand for low-cost, energy-efficient and environmentally friendly technologies. The term biodrying was introduced by Jewell et al. in 1984 while reporting the relevant operating parameters for the biodrying of dairy animal waste [48]. He defined biodrying as (1) a bioreactor used to treat wastes, (2) a combination of physical and biochemical methods that take place in a reactor and (3) biological mechanical treatment processing using a biodrying reactor. Moreover, biodrying is also known as the variance of the aerobic decomposition method, which is used in biological, mechanical treatment plants with the purpose of drying and partly for stabilising the municipal solid waste [47]. Naryono and Soemarno defined biodrying as one of the drying techniques with biological treatment [31].

7.3.2 Advantages of Biodrying

For decades, the biodrying of solid waste has received major attention and extensive investigation by scientists from developed countries. This mainly owes to the advantages that it offers, such as balancing the use of advanced technology that prioritises cost-saving, energy efficiency, and is environmentally friendly. Numerous studies on the operation of the biodrying method have been conducted to improve its operational efficiency, including from the aspects of temperature and airflow control in the biodrying system. The method is also synonymous with increasing the calorific value, thus becoming a focus in the field of waste to energy (WtE) conversion. Several studies on the design of different laboratory-scale biodrying systems have also added to the diversity of innovations in this field. Discussion about solid waste biodrying is still new, especially in developing countries. To date, the method has received scarce exploration in the field of solid waste management in Malaysia, and no previous empirical studies have been conducted on the state of municipal solid waste in the country. In addition, the importance and benefits of this green technology in terms of energy recovery, environmental conservation, integrated solid waste management and cost-saving are highly prominent. Hypothetically, biodrying, which is a method that uses internal energy from organic waste components to produce drying heat through aerobic processes, has a great potential to be applied as a pre-treatment to municipal solid waste in the nation's solid waste management system. Figures 7.12, 7.13, and 7.14 show the different implications of using non-drying, conventional and biodrying methods of solid waste management.

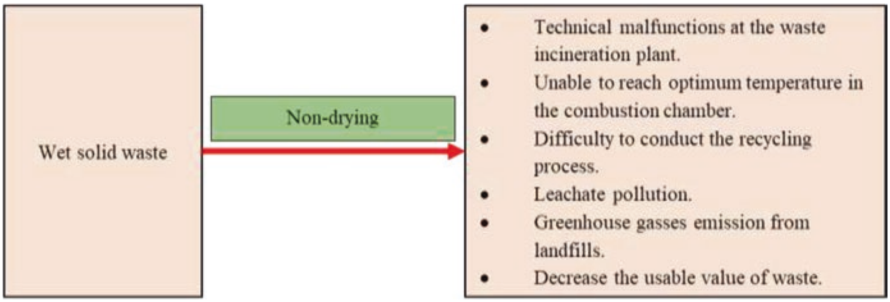


Fig. 7.12 Implication of using the non-drying method

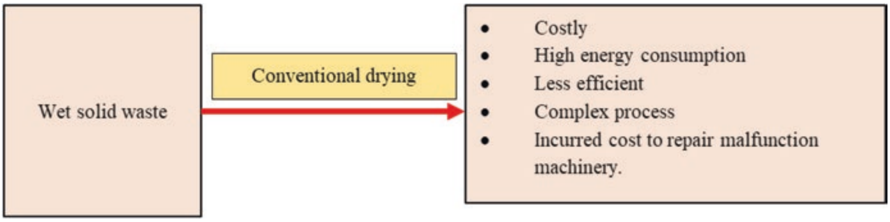


Fig. 7.13 Implication of using conventional drying method

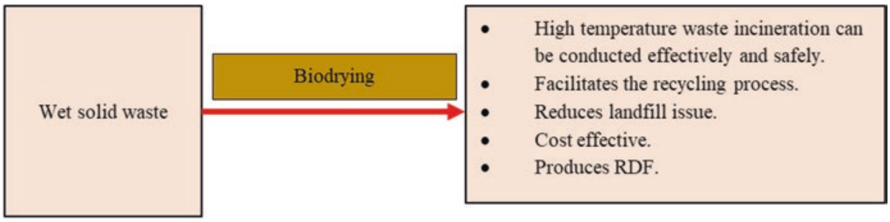


Fig. 7.14 Implication of using biodrying method

7.3.3 Principles of Biodrying Operation

The basic principle in biodrying is the use of internal thermal energy from the activity of microorganisms to decompose the organic waste [41] and is assisted by aeration. Similarly, the biodrying method involves the decomposition of organic matter present in the waste, generating heat with the combination of appropriate aeration, then the evaporation of moisture rate can occur rapidly [36]. When microorganisms consume nutrients, carbon, nitrogen and other elements found in the waste, heat will be produced, which is part of the metabolic activity. The resulting heat-assisted by the aeration system is used to evaporate the moisture content out of the surface of the waste [31]. The evaporation process can be accelerated by using a combination of airflow and natural breakdown processes in the biodrying reactor. In biodrying process, the biodegradable waste materials will decompose mainly to produce heat or energy, carbon dioxide (CO_2) and water (H_2O). Air-heated moisture evaporation helps to increase the calorific value of MSW by reducing its moisture content. Equation (7.1) depicts the aerobic digestion reaction occurring throughout the biodrying process.

$$\text{Organicwaste} + \text{Oxygen}\left(O_2\right) \rightarrow \text{Carbondioxide}\left(CO_2\right) + \text{Water}\left(H_2O\right) + \text{Energy}\left(\text{Heat}\right) \tag{7.1}$$

The main mechanism in the biodrying method is the perspiration or sublimation method that removes the water vapour from the organic waste decomposition activity. The advantage obtained through biodrying method is that it can reduce the moisture content to less than 20% and the CO_2 to reach up to 20%–30% [49]. The moisture content can be reduced through water molecules that evaporate from the surface of the solid waste into the air due to the phase change existence from liquid to vapour or also known as the evaporation method [50]. Volatile water is also transferred to the outside air with the help of airflow from the supplied aeration system [31]. The main mechanism of solid waste mass transfer in biodrying is from the air convection method and dispersion of water vapour molecules that penetrate the pore

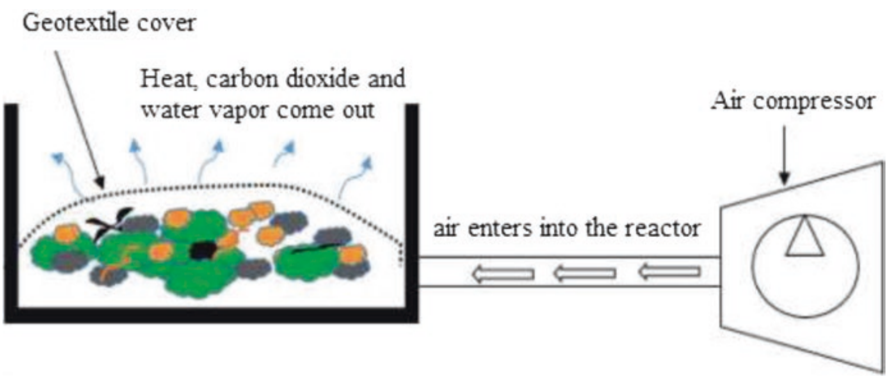


Fig. 7.15 Solid waste biodrying method mechanism [51]

structure of the material [50]. Figure 7.15 shows the mechanism of the solid waste biodrying method diagram.

7.3.4 Biodrying Method Design

The development of a solid waste biodrying reactor is simple and practical, depending on whether it is for a small or large waste capacity. A laboratory-scale biodrying reactor is a design set up to treat wastes in a small capacity intended as an experiment or pilot. The biodrying reactors were developed using a combination of physical engineering and biochemical methods [49]. Physically, biodrying reactors can be designed either using a closed system such as in Fig. 7.16 or a rotary system such as in Fig. 7.17. In practice, it consists of a container or a reactor that is connected to the aeration system, as shown in Fig. 7.18. From a biochemical aspect, the aerobic decomposition of organic materials occurs in the reactor naturally. From the

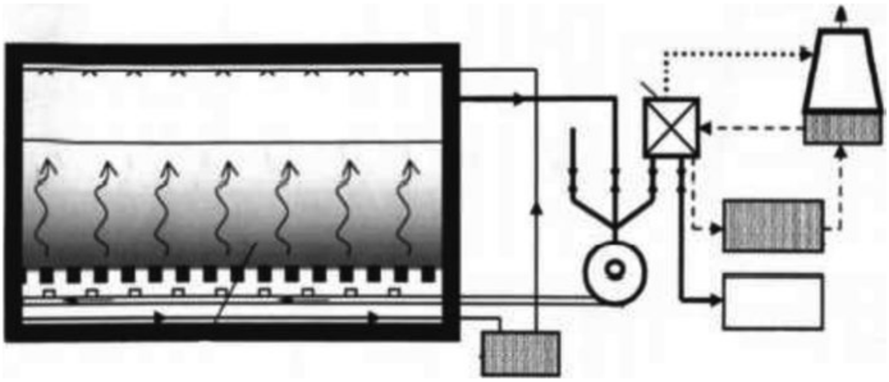


Fig. 7.16 Closed biodrying reactors based on the Herhof system [49]

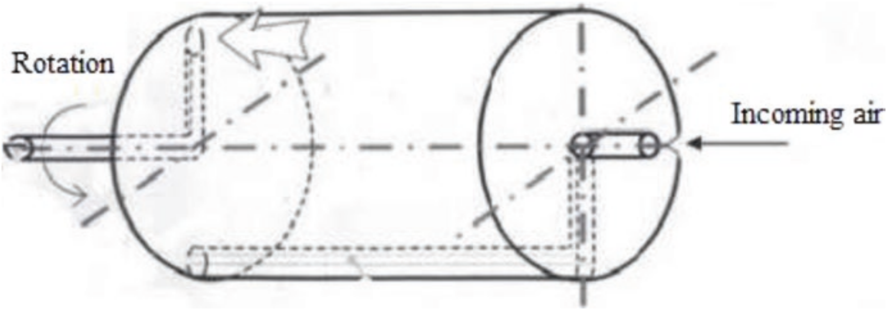


Fig. 7.17 Rotating cylinder biodrying reactor [49]

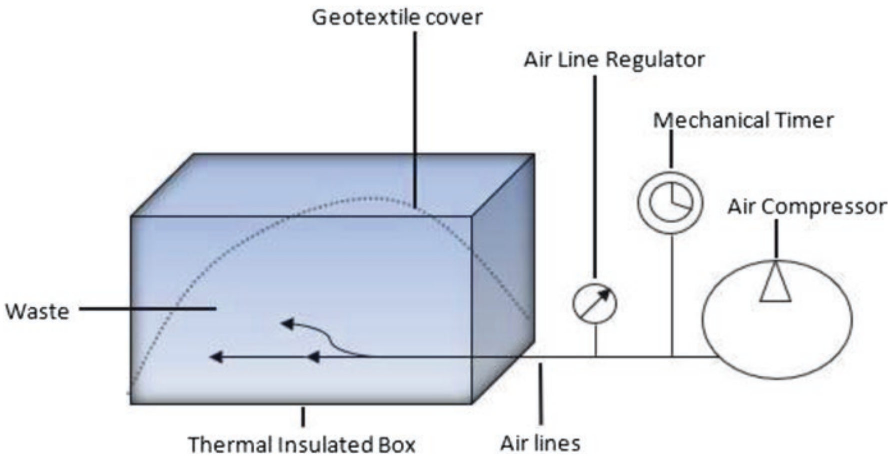


Fig. 7.18 Schematic diagram of a laboratory-scale biodrying reactor [51]

physical engineering aspect, convective moisture control is achieved through the aeration control system [49].

An optimal biodrying can be achieved through an effective reactor design in addition to suitable input material conditions as well as combined with appropriate monitoring and control methods [49]. Among the common technical problems encountered in the biodrying method are as follows:

1. The state of the initial input materials when going through mechanical pre-treatment such as crushing and mixing.
2. The selection of the right reactor, for example, a closed reactor container or rotating cylinder because it will influence the heat transfer mechanism.
3. The use of stirring or mixing methods of waste materials to ensure homogeneity of materials.
4. Designing an effective aeration system to ensure a perfect airflow.
5. Control of incoming airflow rate to ensure adequate oxygen and drying speed.
6. Control of external systems such as temperature and relative humidity to control the psychometric properties of air intake.
7. Management of residual material's retention time in the reactors.

Fig. 7.19 Exterior view of the adiabatic biodrying reactor from a study by the University of Trento, Italy, and Politehnica University of Bucharest, Romania [37]

7.4 Biodrying Design

7.4.1 Reactor Design of Biodrying Study in Italy

Previous scientists have also developed biodrying reactors on a laboratory scale with the purpose of testing the biodrying methods. Based on the influence of temperature and airflow rate on the solid waste biodrying method that was carried out by Adani et al. [36] and Sugni et al. [38], an insulated biodrying cylindrical reactor with a capacity of 148 dm^3 was used. In their investigation, they found that there were weaknesses in the design of diffusion and airflow supply from only one direction where the factors influence the temperature change, material moisture inhomogeneity and energy content in the final product. However, the researchers did not explain in detail the design [43].

Researchers who have been very active in the field of solid waste biodrying at the University of Trento in Italy since 2003 are Rada et al. [37] and Negoi et al. [42], who have developed an in-laboratory biodrying reactor design as their pilot model. This pilot reactor is an adiabatic box that is placed on an electronic scale for monitoring the waste mass loss during the biodrying method. The travel airflow method will be sent into the reactor through a steel diffuser which is placed at the bottom of the box. Figure 7.19 shows pictures of biodrying reactors used in solid waste biodrying at the University of Trento, Italy, and also the Politehnica University of Bucharest, Romania [37].

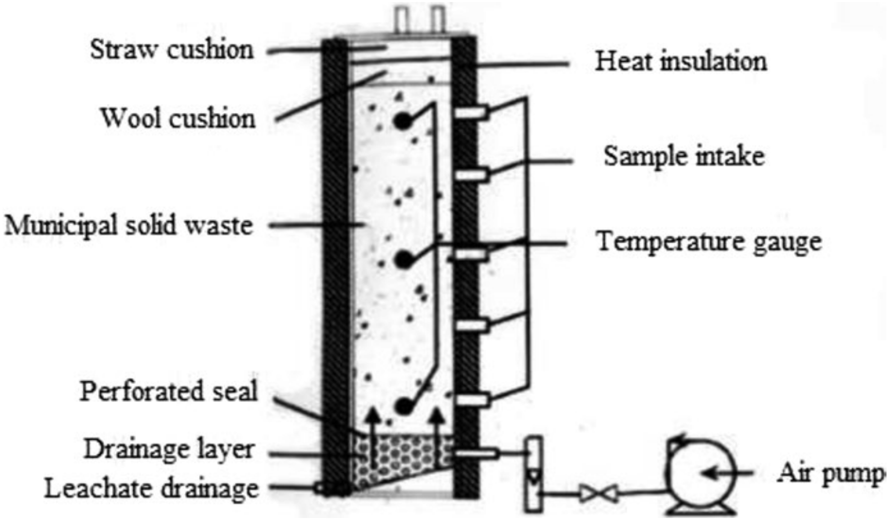


Fig. 7.20 Cylindrical biodrying reactor from the study by Tongji University, Shanghai, China [41]

7.4.2 Reactor Design of Biodrying Study in China

A group of researchers from Tongji University in Shanghai, China, have also developed a cylindrical biodrying reactor design for municipal solid waste biodrying method by combining two technologies which are hydrolytic and aerobic, to remove water from the waste [41]. With the goal of improving the operational parameters of the process, this study looked at the biodrying performance of distinct scenarios that had similar operations during the aerobic stage but varying ventilation frequencies or temporal spans during the hydrolytic stage. The laboratory-scale column reactor was constructed using polyvinyl chloride (PVC) with a height of 1200 mm, and the inner diameter of the cylinder was 400 mm. For thermal insulation purposes, the reactor was wrapped with 100-mm-thick cotton fibre around its outer wall. For leachate drainage and air distribution, a 100-mm-high layer of crockery balls (diameter around 5 mm) was positioned at the base of each column. A 2-mm mesh perforated baffle was added above the balls to support and help ventilate the waste. Five 200-mm-apart sampling intake ports were installed above the baffle. Two layers of straw and cotton were placed over the wastes to prevent heat loss and vapour condensation. A whirlpool pump and a gas-flow meter were utilised for aeration. Figure 7.20 shows a schematic diagram of the biodrying reactor from Tongji University, Shanghai, China.

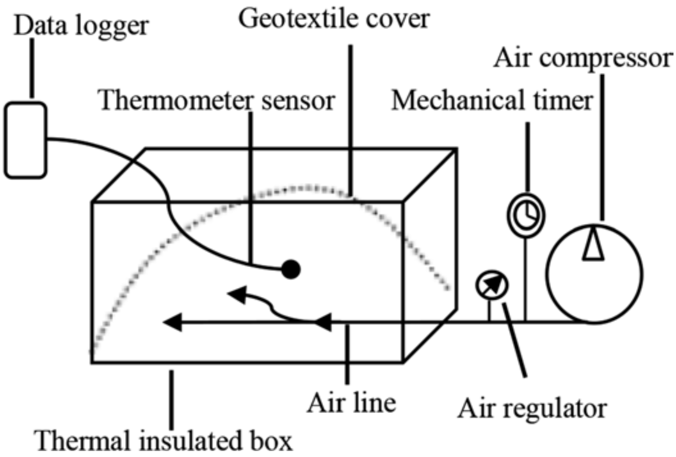


Fig. 7.21 Schematic of the lab-scale biodrying reactor [51]

7.4.3 Case Study: Universiti Kebangsaan Malaysia

7.4.3.1 Lab-Scale Reactor Design

The biodrying reactor (Fig. 7.21) was located within the Faculty of Engineering and Built Environment at Universiti Kebangsaan Malaysia (UKM). To prevent heat loss during the biodrying process, the reactor was made of high-density polyethylene (HDPE) for the outer wall and polyurethane (PU) for the inner wall. The reactor had a capacity of 50 L and external dimensions of 600 mm length × 400 mm width × 360 mm height, as well as internal dimensions of 540 mm length × 345 mm width × 275 mm height. For ventilation, the reactor was outfitted with a 2 horse power air compressor (Brand: Swan, Model: SVP-202). The air compressor was linked to a digital mechanical timer and valve to regulate the ventilation system's air interval time. The air pressure entering the biodrying system was controlled using an air flow regulator attached to the reactor. A tubing system was used to connect the various parts of the biodrying reactor. External connections were made with 12 mm diameter tubing, while interior connections were made with 8 mm diameter tubing. The same level of vertical moisture distribution homogeneity was achieved by inverting the air-flow direction as by turning the waste matrix [52]. The waste sample in the biodrying system was covered with a nonwoven, thermally resistant polypropylene geotextile with a specially designed surface treatment that allowed rain to easily flow off the exterior surface. The porous nature of the geotextile cover, on the other hand, allowed moisture inside the reactor to rapidly evaporate. In the reactor, a temperature sensor was connected to a data logger, enabling for the recording and monitoring of temperature data within the biodrying system.

Table 7.5 Composition of SMSW

Components	Percentage by weight	Material used
Food waste	47	Food waste is taken from the cafeteria (cut into 6-mm pieces)
Paper	15	Shredded paper is taken from administration office (less than 3 mm wide and 25 mm long)
Plastic	14	Plastic (less than 3 mm wide and 15 mm long)
[a]Glass	3	N/A
[a]Metal	4	N/A
Textile	3	Textile (less than 3 mm wide and 10 mm long)
Wood	4	Wood shavings from a pet shop
[a]Leather/ rubber	1	N/A
Other	9	Diapers (less than 3 mm wide and 10 mm long)

[a]Glass, metal and leather/rubber were not included because these are non-combustible materials and can be recycled

Table 7.6 Management of ventilation periods

Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
5 min on 3 h off	10 min on 3 h off	15 min on 3 h off	20 min on 3 h off	30 min on 3 h off
3.00 p.m. on 3.05 p.m. off	3.00 p.m. on 3.10 p.m. off	3.00 p.m. on 3.15 p.m. off	3.00 p.m. on 3.20 p.m. off	3.00 p.m. on 3.30 p.m. off
6.05 p.m. on 6.10 p.m. off	6.10 p.m. on 6.20 p.m. off	6.15 p.m. on 6.30 p.m. off	6.20 p.m. on 6.40 p.m. off	6.30 p.m. on 7.00 p.m. off
9.10 p.m. on 9.15 p.m. off	9.20 p.m. on 9.30 p.m. off	9.30 p.m. on 9.45 p.m. off	9.40 p.m. on 10.00 p.m. off	10.00 p.m. on 10.30 p.m. off
12.15 a.m. on 12.20 a.m. off	12.30 a.m. on 12.40 a.m. off	12.45 a.m. on 1.00 a.m. off	1.00 a.m. on 1.20 a.m. off	1.30 a.m. on 2.00 a.m. off
3.20 a.m. on 3.25 a.m. off	3.40 a.m. on 3.50 a.m. off	4.00 a.m. on 4.15 a.m. off	4.20 a.m. on 4.40 a.m. off	5.00 a.m. on 5.30 a.m. off
6.25 a.m. on 6.30 a.m. off	6.50 a.m. on 7.00 a.m. off	7.15 a.m. on 7.30 a.m. off	7.40 a.m. on 8.00 a.m. off	8.30 a.m. on 9.00 a.m. off
9.30 a.m. on 9.35 a.m. off	10.00 a.m. on 10.10 a.m. off	10.30 a.m. on 10.45 a.m. off	11.00 a.m. on 11.20 a.m. off	12.00 a.m. on 12.30 a.m. off
12.35 a.m. on 12.40 a.m. off	12.10 a.m. on 12.20 a.m. off	1.45 p.m. on 2.00 p.m. off		

7.4.3.2 Waste Sample Preparation

Based on data from the National Solid Waste Management Department (2005), synthetic municipal solid waste (SMSW) was prepared to simulate the typical composition, by weight, of municipal solid waste generated in Malaysia. Table 7.5 shows the SMSW generated for the composition of this case study. Synthetic municipal solid waste was made by weighing the required amounts of waste components and then manually mixing them together until the moisture was uniformly distributed.

7.4.3.3 Experimental Set-Up

Five sets of SMSW samples, weighing approximately 12 kg each, were processed at five different air interval times, which were regulated by a mechanical timer. In this case study, replication involves repeating a biodrying process with different ventilation periods. The ventilation system was based on the extract-only principle, which required a basic mechanical ventilation system that uses ducts and fans to extract air from the ventilated space. An air compressor pumped air into the reactors in line with each reactor's ventilation schedule. The following ventilation times were used: 5 min of ventilation followed by 3 h of no ventilation (Reactor A), 10 min of ventilation followed by 3 h of no ventilation (Reactor B), 15 min of ventilation followed by 3 h of no ventilation (Reactor C), 20 min of ventilation followed by 3 h of no ventilation (Reactor D) and 30 min of ventilation followed by 3 h of no ventilation (Reactor E). The management of ventilation periods during the biodrying process is shown in Table 7.6.

For structural stability and to keep air spaces in the waste matrix, wood shavings were used as a bulking agent. To avoid the formation of a moisture gradient, the waste was manually turned every 2 days. It was necessary to collect moisture content samples while turning process to prevent interruptions to the microbiological process during biodrying. After every turning activity, approximately 100 g of waste was collected at three different levels and transported to the UKM laboratory for a comprehensive analysis of moisture content. This prevented microbiological processes from being disrupted during biodrying. The American Society for Testing and Materials (ASTM) E 989–88 was used to estimate the waste moisture content (wet basis). Measurement of moisture content was conducted in triplicate for each sample. The moisture content was measured on days 1, 3, 5, 7, 9, and 11, with the final measurement on day 14, on alternating days beginning on day 1. The biodrying process was carried out over a 14-day period, which corresponded to the typical biodying duration [37]. The temperature was measured every day using a thermometer with sensor probes in the middle of the waste core.

7.4.3.4 Results and Discussion

7.4.3.4.1 Moisture Content and Mass Loss

The decrease in moisture content for reactors A, B, C, D, and E at five different ventilation times was 67% to 33.91%, 65.57% to 11.91%, 67.96% to 20.57%, 62.31% to 15.44% and 64.56% to 13.23%, respectively (Fig. 7.22). Based on the results presented in Fig. 7.23, reactor B had the highest moisture reduction of 81.84%, followed by reactors E (79.51%), D (75.22%), C (69.73%) and A (49.39%).

For the biodrying process, the ventilation scheme with 10 min of aeration and 3 h without aeration for 14 days produced the most optimal results. This was followed by ventilation times of 30 min, 20 min and 15 min, whereas ventilation for 5 min showed the lowest percentage reduction in moisture content. Based on this case

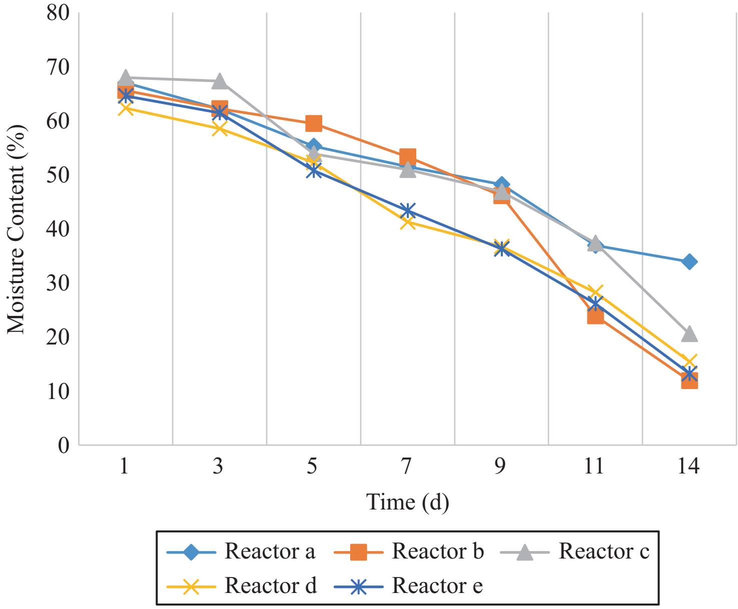


Fig. 7.22 Moisture content reduction

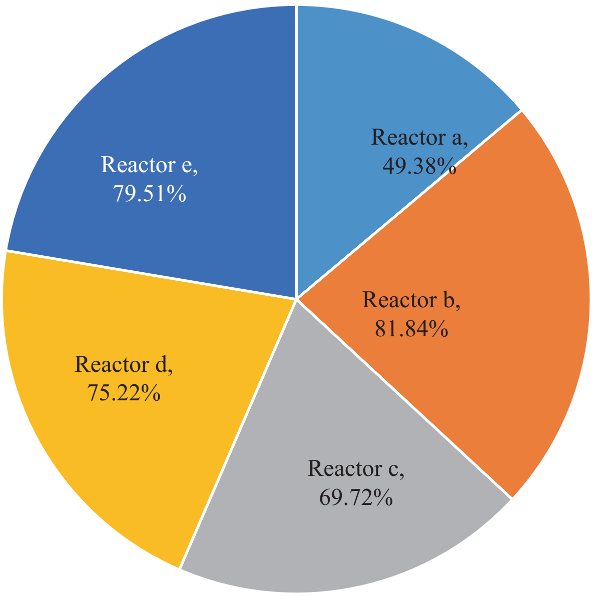


Fig. 7.23 Percentage of moisture content reduction

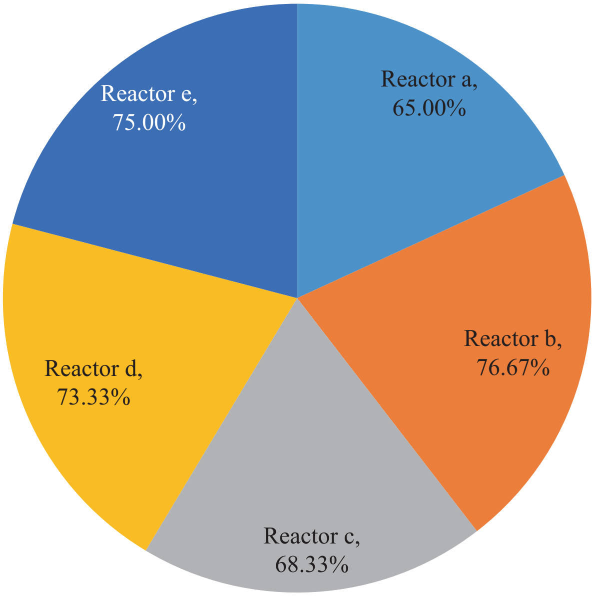


Fig. 7.24 Percentage of mass loss reduction

study, longer ventilation does not result in optimal waste drying. This result may be influenced by microorganisms, which are very significant to the process of biodrying and are affected by factors such as nutrients, pH, light, humidity and temperature [53]. Microorganisms in the waste samples need to be controlled so that the process of biodrying can occur quickly and effectively. Prolonged ventilation times may cause microorganism activity imbalances or disruptions, whereas very short ventilation times may prevent adequate heat removal from the reactor. These findings indicate that heat convection influences the evaporation process and that the exothermic process of aerobic waste degradation requires the management of ventilation flow to effectively remove heat from the reactor.

Shorter ventilation time created wet conditions in the sample for an extended period of time, consequently producing a large number of maggots. Reactor A contained waste samples that were still wet on day 10, whereas reactors B, D and E had samples that appeared dry on day 9. This occurred due to insufficient ventilation in reactor A; heat generated by microorganism activity could not be released from the reactor and remained trapped beneath the reactor's cover. This situation triggered high humidity inside the reactor and thus deterred the drying process. The prolonged drying process lengthened the time that microorganisms were alive and active because such reactions require water at certain levels as a medium. Hence, the drying process might reduce or cease the action of enzymes or bacteria. As a result, optimum ventilation time is important to ensure that the drying process works efficiently.

The percentage of mass lost in each reactor is presented in Fig. 7.24. These findings show more than 50% reduction in waste weight. On the other hand, based on other researchers' findings, weight loss of slightly more than 25% after approximately 2 weeks and of almost 30% after 1 month [37]. There was a 70% reduction in weight loss after hydrolytic and aerobic biodrying [41]. In this case study, reactor B demonstrated the greatest mass reduction, followed by reactors E, D, C and A. These findings are comparable to the moisture content reduction discussed above because mass loss is caused by a decrease in water content during biodrying as well as partial degradation of organic matter. Weight reduction of waste through biodrying is beneficial because reducing the transportation load can also reduce transportation costs.

7.4.3.4.2 Influence of Temperature

The efficacy of biodrying is determined by temperature management. The normal temperature pattern of the biodrying process was observed in this case study, i.e. the temperature increased in the first week and subsequently dropped to external ambient temperature [39]. The appropriate management of operating parameters such as air flow rate and temperature could achieve solid waste drying in very short periods of approximately 8–9 days [38]. According to previous research, controlling the temperature and air flow rate throughout the biological process can result in waste biodrying and stabilisation [36]. Temperature, on the other hand, is difficult to regulate because it is dependent on the activity of the microorganisms in the biodrying reactor. Mesophilic temperatures, between 35 °C and 40 °C, or moderately thermophilic temperatures of 40 °C–45 °C are more relevant for biodrying than are

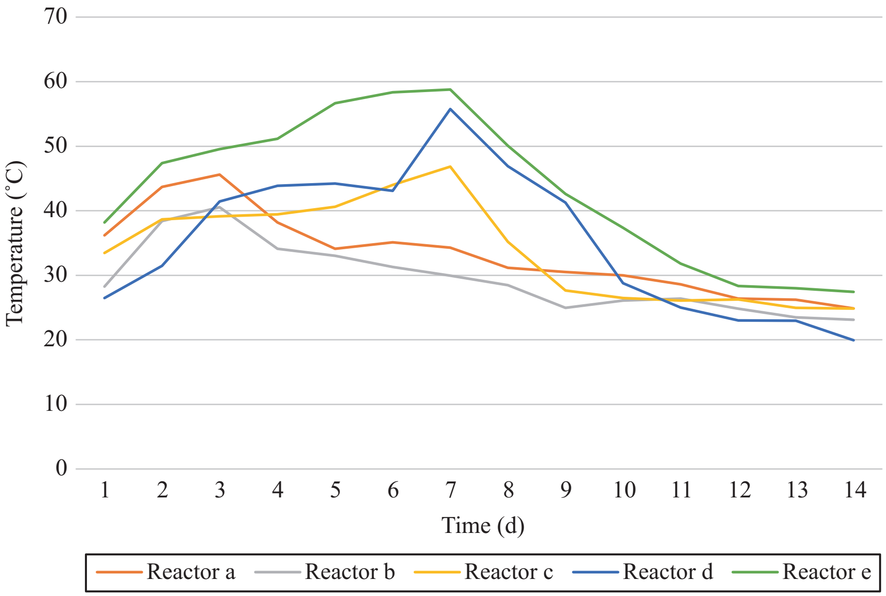


Fig. 7.25 Temperature trends during biodrying

thermophilic temperatures of 55 °C–70 °C. Specifically, it was reported that high temperature and low air flow could slow down the drying process.

In this case study, the temperature was monitored daily for 14 days to observe the microbial activity that occurred during biodrying. As showed in Fig. 7.25, the increase in temperature occurred between day 1 and day 3 for reactors A and B, indicating that a very vigorous biodegradation process by microorganisms occurred during that time. The thermophilic phase (above 55 °C) was not achieved during the initial days because the water content was still excessively high. On day 3, the highest temperatures for reactors A and B were 45.6 °C and 40.5 °C, respectively. The temperature steadily dropped to 34.1 °C and 33.0 °C on day 4 of the experiment., respectively. Temperatures remained mesophilic until day 8, at which point they dropped to between 27.5 °C and 23.1 °C, which indicated that microbial activity had been severely diminished or had completely ended. The temperature trends in reactors A and B showed that a short ventilation time does not generate a high temperature. However, a short ventilation time, such as 5 min, caused the sample to be very moist, limiting the increase in temperature to an acceptable level. The sample conditions became drier after passing through a moderately thermophilic phase in Reactor B, demonstrating a typical temperature trend for biodrying. Temperature trends in reactors C, D, and E differed from those in reactors A and B. The temperature rose significantly from the first to the seventh day. Reactors D and E followed the same pattern, exhibiting rapid, tremendous growth for 7 days. This finding indicates that the biodegradation process takes a long time, which may affect the calorific value and degree of stability of the final product, particularly the RDF [36]. The prolonged biological process for these three reactors led to significant degradation of the organic fraction in the waste [39]. This showed that long ventilation times created an intensive biodegradation process, which can be advantageous for releasing heat from the sample. After day 7, the temperature dropped slightly for reactors C and D until days 9 and 10, respectively. Reactor E showed a slight decrease from day 7 until day 14. The temperature in reactor C showed a steady decrease after day 9 compared with reactors D and E, in which a steady decrease started later, on day 12. Reactors D and E also recorded a thermophilic temperature of 55.8 °C and 58.8 °C, respectively, on day 7. Biodrying requires a temperature range of 40 °C–70 °C for proper microorganism growth; hence, an adequate aeration system is used in the biodrying design to regulate the reactor's temperature [42].

7.4.3.5 Electricity Consumption

The cost of drying is one of the most significant aspects to consider when selecting a drying method. Many parties, particularly the government, can benefit from biodrying by minimising operating and maintenance costs. The biodrying process uses internal energy to dry the waste, unlike conventional drying techniques, which require expensive equipment and are costly to operate. Although conventional drying has the advantage of drying waste more quickly, biodrying is a better option in terms of both economics and the environment.

Table 7.7 Estimated electricity consumption

Reactor	Cost of electricity consumption during the biodrying process (MYR)
A	5.29
B	10.58
C	15.87
D	18.52
E	27.78

The amount of electricity consumed during biodrying was calculated in order to determine the cost of electricity for each ventilation scenario. Equation (7.2) was used to calculate the cost of electricity for each ventilation period according to the Tenaga Nasional Berhad (TNB) billing calculation, using the most recent cost of electricity in Malaysia for Low Voltage Industrial (Tariff D) of 0.38 Malaysian Ringgit (MYR)/kWh. Table 7.7 shows the estimated cost of electricity consumption for each biodrying reactor, where air compressor horse power (HP) is equal to 2.

$$\text{Costofelectricity} = HP \times 0.746 kWh \times \text{tariffrates} \times \text{numberofhoursused} \times \text{day}. \tag{7.2}$$

According to Table 7.7, reactor A used the least amount of electricity, followed by reactors B, C, D, and E. However, reactor B has the most effective ventilation parameters in terms of optimal drying efficiency and electricity cost reductions. Despite the fact that the moisture content reduction for reactors B, D, and E was similar, the cost difference between reactor B and reactors D and E was almost double.

7.4.3.6 Conclusion

In conclusion, ventilation periods are an important factor to enhance the effectiveness and efficiency of the biodrying process. The efficiency and speed of the biodrying process might be improved with optimal ventilation intervals, while operational costs and energy consumption would be reduced. Ventilation intervals, on the other hand, are essential for managing the heat and humidity of the process. As a result, in this case study, a high reduction in solid waste moisture content of 81.8% was achieved with 10 min of ventilation every 3 h during the biodrying process. In addition, a reduction in the use of mechanical supports in biodrying systems can contribute towards more green technologies, sustainable and cost-effective solutions. It is important to note that biodrying research for municipal solid waste in Malaysia is still in its infancy and has yet to be put into practise in a waste management system. Other aspects of the biodrying process, such as how the content of municipal solid waste affects the calorific value and volatile solids during biodrying, should be investigated further in relation to the characteristics of municipal solid waste in Malaysia, so that solid waste can be converted to beneficial renewable energy.

7.5 Factors Influencing Biodrying Method

Biodrying is a biological and physical method that is influenced by several important factors that influence the efficacy of the method. Among the important factors that have been studied by previous scientists in this field are moisture content, airflow rate, volatile organic content, temperature, heat, energy values, microorganisms, enzymes and heavy metals.

7.5.1 Moisture Content

Moisture content is the quantity of water contained in a material. In biodrying, moisture content is the main factor observed in determining the effectiveness of the method [54]. The residual moisture content in the biodrying method should be examined from the beginning of the sampling method until the end of the method. The range of initial moisture content rate of solid waste for the biodrying method is between 60% and 65% [53]. If the waste or residual moisture at the initial stage is too low, which is below 40%, it can affect the microbiological activity, which will cause the biodegradation to occur slowly due to the low presence of water which is required in the microorganisms metabolic method [53]. Contradictorily, if the moisture rate exceeds 65%, it is very likely that the anaerobic method can occur due to having too much water compared to the air intake [53]. Therefore, the role of stabilising or controlling the moisture content in the initial stage of biodrying method is very important in controlling other parameters in the biodrying method.

7.5.2 Aeration

Although biodrying uses a natural drying method, supportive aids such as aeration are needed in order to speed up the method. Aeration in the biodrying system provides a media flow for mass and energy that enables the removal of water content, distribution of heat transfer, removal of excess heat and regulation of matrix temperature [49]. Because air movement is critical in reducing MSW weight and moisture content, the aeration system is an unavoidable component of the biodrying process. The airflow rate is of concern because it is related to waste temperature and weight reduction during the drying process [55]. Airflow rate is a critical factor that requires proper control during the biodrying method in response to the exhaust gas temperature in order to fully utilise metabolic heat for evaporation [52]. Low aeration rates result in a decomposition that does not emphasise the removal of high moisture content where the method is similar to the composting method. High aeration rates will speed up the method of cooling the materials and stop the microbiological activity. The management of aeration systems in the solid waste biodrying method varies according to the complexity of the method and reactor design [49].

Most of the large-scale biodrying plants designed the airflow at the bottom where the solid waste site is placed to facilitate the matrix temperature control [49]. The influence of airflow in the biodrying method has proved that if the state of the waste material is static and the airflow is either only one way or in one direction, then the degree of temperature will exist in the waste resulting in the homogeneous deficiency in the waste moisture and energy content in the final product [38]. In addition, the management of optimum operating parameters, especially on the airflow rate and temperature factors, can shorten the retention time of the biodrying method up to 8–9 days only [38].

7.5.3 Temperature

Based on the municipal solid waste biodrying that was conducted in Romania, the temperature range for good growth of microorganisms for biodrying is between 40 °C and 70 °C [42]. For the second and third days of the biodrying method, the temperature will normally increase, reaching between 37.8 °C and 48.9 °C and can reach up to 55 °C if the organic fraction is sufficient [49] as well as the airflow rate is optimised [52]. The temperature will increase until it reaches 60 °C and will reduce again to about 43 °C in the following days [35]. The method of flipping the materials in the reactor, which aims to ensure uniformity of moisture distribution in the material, also influences the temperature change. The temperature after the flipping method will usually drop sharply but with increase again within 1–2 days and return to the range between 37.8 °C and 48.9 °C. The mesophilic temperature condition of 35 °C and medium thermophilic temperature which is between the range of 40 °C and 45 °C are more effective temperatures compared to the thermophilic temperature of 55 °C–70 °C in the biodrying method, especially for decomposition [56]. The size of the reactor also influences the temperature, where for a small-sized reactor, the temperature can increase up to 50 °C–62 °C, while for a large-sized reactor, it can reach up to 70 °C [31].

7.5.4 Calorific Value

In the biodrying method, the reduction in moisture content in the solid waste can produce an increase in the calorific value by 30%–40% [53]. Therefore, the importance of removing most of the water content in solid waste is to increase the energy content or calorific value of the waste before it is used for energy production [39]. Calorific value is a calculation that is used in determining the energy in a material. This parameter is important in the conversion of waste to energy because the increase in calorific value can convert waste into a fuel source for energy generation use. The calorific value of municipal solid waste in Malaysia is in the range of 1200 kcal/kg to 1400 kcal/kg, while the calorific value of fuel increases to 4000 kcal/

kg to 4500 kcal/kg [6]. Solid waste that has a minimum calorific value of 11,600 J/g or 2772 kcal/kg can be burned continuously and stably without needing additional fuel compared to solid waste that has a smaller calorific value where additional fuel is needed [57]. Municipal solid waste such as plastic and paper has high calorific value content causing the wastes to be used in biodrying methods.

7.5.5 Microorganisms Activity

Microorganisms activity also plays an important role in biodrying method. Stopping the activity of the microorganisms from continuing to occur after the biodrying method can prevent unwanted problems such as foul odour production, leachate and biogas production, environmental pollution and health disturbances towards workers and residents [58]. The decomposition condition of organic materials present in the solid waste influences the activity of the microorganism's methods [39]. In this case, the reduction of residual moisture content can restrict the activity of the microorganisms, thus reducing the negative impact, especially during transportation and storage methods. Nevertheless, this factor has received less attention from previous researchers who have focused more on the energy aspect [59]. Measurement of the microorganism's activity potential can be done by detecting the oxygen uptake or absorption rate of the waste under uniform conditions by analysing the Dynamic Respiration Index parameter [60, 61].

7.6 Biodrying Facilities in Malaysia and Abroad

In developed countries such as Germany and Japan, the tendency towards preserving the concept of bioengineering is increasing in line with technological advancements. In fact, natural methods such as recycling, composting and biodrying have been a prominent practice in these countries as such natural treatment methods are believed to have longitudinal advantages in terms of energy resource acquisition, environmental conservation, economic saving and global ecosystem harmony. Direct fieldwork observation was conducted at three biodrying plants: two plants that operated temporarily in Malaysia located at Semenyih, Selangor and Jalan Klang Lama, Petaling Jaya; and a large-scale biodrying plant at Kömürcüoda, Turkey. The solid waste treated at these biodrying plants is municipal solid waste consisting of food waste, papers, plastics, wood dust and domestic waste, as well as hazardous waste.

Results from the observation indicate that a thorough and comprehensive initial preparation is necessary before implementing a large-scale biodrying system. This is to avoid future problems that could interfere with the speed of the biodrying time period. Among the findings identified pertaining to the practical feasibility to operate the biodrying system are:

1. A large and spacious area to develop a realistic large-scale biodrying system.
2. An effective ventilation system that allows air to be released evenly.
3. Safety concern from the aspect of energy resistance that can interfere with the operation of the system especially those involving the use of energy such as mechanical ventilation.
4. Utilisation of municipal solid waste landfill cover features to optimise heat-trapping during the biodrying process.
5. Adding other materials as a catalyst accelerating the waste decomposition process as well as the absorption of moisture content.

7.6.1 Biodrying Plant at RDF Plant, Semenyih, Selangor

Biological or natural solid waste drying is a relatively new method in the Malaysian solid waste treatment system. In September 2010, CONVAERO Malaysia Sdn. Bhd. (a subsidiary of CONVAERO GmbH) was established with the objective to provide expertise in the biological field of solid waste drying in order to produce high-quality fuel from municipal solid waste as well as biomass. The company aims to be the market leader in the country that offers reliable, efficient and cost-effective

Fig. 7.26 Entrance gate to the Solid Waste Resource Recovery Centre (RDF Plant), Semenyih, Selangor

Fig. 7.27 Heaps of municipal solid waste for biodrying process

Fig. 7.28 Ventilation pump for the biodrying system

solutions to solid waste problems that can be implemented faster than other existing concepts available in the market.

The company's first waste drying project was the Solid Waste Resource Recovery Centre located at Semenyih, Selangor. Also known as the Refuse Derived Fuel (RDF) plant, this biodrying project served as a treatment of choice for waste and sludge disposal. From an interview with CONVAERO Malaysia Sdn. Bhd., the municipal solid waste biodrying project did not receive much response from the parties involved due to internal factors such as the top management's preference towards more advanced technologies that are proven effective in developed countries such as incinerators. In addition, limited space to conduct the biodrying process of more than 1000 tonnes of solid waste sent to the plant was another contributing factor to its failure. Due to these constraints, the waste biodrying project at the RDF plant Semenyih operated only for 4 months, from August 2011 to December 2012. Figures 7.26, 7.27 and 7.28 show several photographs, taken during a fieldwork visit to the RDF plant in Semenyih.

Fig. 7.29 Ventilation pipes

Fig. 7.30 Waste heaps covered with geotextile

7.6.2 Biodrying Plant at Jalan Klang Lama, Petaling Jaya, Kuala Lumpur

A fieldwork observation was also conducted at another biodrying plant owned by CONVAERO Malaysia Sdn. Bhd. It is located at Jalan Klang Lama, Petaling Jaya. It houses two biodrying reactors with a capacity of approximately 200 tonnes of waste per reactor. The first reactor contains food and wood wastes mixed with sludge. This sludge mixing aims to maximise the microbiological process so that the biodrying process can happen more effectively and productively. In contrast, the second reactor contains municipal solid waste mixed with wood waste. Wood waste serves as a bulking agent that increases the cavities in the waste heap and absorbs excess moisture [62].

From the technical perspective, the reactors consist of two porous pipelines and an air blower that supplies air to the waste heap (see Fig. 7.29). This provides oxygen to help boost and accelerate the decomposition process of organic waste while controlling the temperature in a heap [63]. The ventilation operation of the waste heap can be controlled using an automatic timer connected to the air blower. This gives control to the airflow rate to produce the desired temperature profile in the organic waste heap [64]. Each waste heaps stored at this plant has a size of 5–6 m in height, 13 m in length, and 7 m in width. It is covered with a geotextile cover specially designed by the company (see Fig. 7.30) to trap heat and prevent external water leakage. Each waste heap is also equipped with a sensory temperature detector connected to a computer programme to monitor any temperature changes during the biodrying process.

The biodrying plant also houses a cabin equipped with computers that are connected to the reactors to monitor the operation of the biodrying reactors, two storage stores and a shed for dry waste storage. There is also an excavator that is used to turn the waste heaps. The turning process is periodically performed to supply oxygen to the organic heaps while breaking the organic waste clumps into smaller sizes that will boost the decomposition action by microorganisms or other decomposing organisms. It also plays an important role in improving the porous properties of organic materials. This is to prevent sedimentation and compaction from occurring on the wastes while releasing any heat, water vapour and gases trapped in the waste heaps. The biodrying operation is monitored and controlled through the Bio-Dry ™ Control system.

All data obtained from the fieldwork observations conducted at both biodrying plants were combined because these plants use similar concepts and mechanisms to treat municipal solid waste. The fieldwork observations done at these two temporary plants provided a realistic preliminary picture of the concept of biodrying as a method for municipal solid waste management. Although the biodrying project was challenging due to space constraints and limited cooperation from the authorities, the effectiveness of solid waste drying can still be seen where it uses most of the metabolic activity from the waste materials. The observation results also indicate that a thorough and comprehensive preparation should be done before implementing a large scale biodrying system.

Fig. 7.31 Waste heaps covered with a geotextile membrane

Fig. 7.32 Turning process using machine

Fig. 7.33 Automatic machine to remove the geotextile membrane

Fig. 7.34 Ventilation pores

7.6.3 Biodrying Plant at Kömürcüoda, Turkey

Further fieldwork observation was conducted involving a biodrying plant located at the outskirts of Kömürcüoda, Turkey, which is on the Anatolian side of Istanbul. The biodrying plant comprises 0.4 million square meters of land located within the former Kömürcüoda solid waste landfill, which has approximately 15 million tonnes of wastes that were buried since 2009 after reaching its maximum capacity. The area is currently being developed as a waste to energy (WtE) treatment facility, a mechanical biological treatment (MBT) facility, and waste recycling operated by HEREKO, Inc. Municipal solid waste in Istanbul is managed under the Istanbul Environmental Protection and Waste Processing Corporation (ISTAC Corp.) which was established on 28 November 1994.

The Kömürcüoda solid waste biodrying plant receives approximately 8000 tonnes of waste capacity per day. It has a total of 12 municipal solid waste heaps that are processed through the biodrying method. Each heap consists of between 600 and 800 tonnes of waste, with its size being 15 m long, 10 m wide, and 7–8 m high. These heaps are neatly covered with a geotextile membrane fastened to the wall (see Fig. 7.31). The turning process is performed three times a week using a more practical and modern machine (see Fig. 7.32). The plant is also equipped with an automatic machine to remove the geotextile membrane (see Fig. 7.33). Meanwhile, the ventilation system is supplied by an air pump via ventilation pores drilled beneath the floor, with each heap having two rows of ventilation pores approximately 15 meters long (see Fig. 7.34).

The opportunity to conduct direct fieldwork observation at a large-scale biodrying plant situated within a suburb in the Anatolian part of Istanbul has been a meaningful and rewarding experience. Its strategic location combined with an array of solid waste treatment methods such as the waste to an energy treatment facility, biological, mechanical treatment and waste recycling demonstrate its exemplary integrated solid waste management system. The plant also has one of the most systematic and complete biodrying systems equipped with facilities such as an underfloor ventilation system, partition wall for each waste heap, automatic machinery to remove the geotextile membranes and waste turning machinery.

The sampling process was done two or three times a week after the waste turning activity. The initial moisture content for municipal solid waste in Kömürcüoda was around 50%, and the average final result from the 4 weeks of biodrying showed that the moisture content had reduced up to 15%. The final wastes dried through this process were then sent to cement factories to be used as fuel. The temperature of each waste heap was monitored and controlled using the Biodry™ Control system to ensure that it stayed between the optimum temperature of 40 °C to 45 °C and did not exceed the 60 °C temperature cap.

Significant differences in the characteristics and composition of municipal solid waste in Turkey and Malaysia thus necessitate a preliminary study on the application of biodrying method to the high humidity sample of municipal solid waste in Malaysia. During the fieldwork, there were two types of newly developed geotextile membranes that were tested for their efficiency to accelerate the waste drying process. This suggests that geotextile cover is one of the important components to improve biodrying efficiency where the use of the new geotextile membranes is predicted to accelerate the drying time a week earlier as compared to the existing geotextile.

Furthermore, the Kömürcüoda biodrying plant uses a mechanism that is more systematic than the ones used by other plants investigated in this study. However, the biodrying concept remains the same, where the main process revolves around the reactions within the metabolic activity of the municipal solid waste aided by the ventilation system. For large-scale plants, the underfloor ventilation system can provide uniform, effective and practical air production. The observation results show that the operation of such a ventilation system is more tidy, simple and organised. A total of four rows of ventilation holes, each 1 cm in diameter, were drilled at the area where the waste heap was stored. Constant and controlled air was then released from these holes to ensure that the decomposition process happened in an aerobic state to reduce foul odour and boost the biodrying process. Such concept of ventilation system management is also applied in a biodrying facility located at ZutpHen, Netherland [45].

7.7 The Importance of Solid Waste Biodrying

The national solid waste management policy aims to create a solid waste management system that is comprehensive, integrated, cost-effective, sustainable and accepted by the general public that gives benefits to the well-being and survival of the community, especially future generations. In this regard, the development and implementation of an integrated solid waste management plan involve a combination of options and technologies that are appropriate to the local laws and conditions [65]. Thus, employing biodrying as a solid waste pre-treatment before treating it using other solid waste treatment methods is seen as a potential solution to the problem of municipal solid waste condition in Malaysia that is too wet. Moreover, the high moisture content in local solid waste is also a major constraint to the success of heat treatment technology. The vital key factor to consider in the selection of technology is the amount of energy required to treat waste as well as its environmental impact [6]. This is in line with the 'National Waste Management and Planning Strategy' in Romania, which considers the pre-treatment method as complementary to incineration, thus serving as one of the important techniques in integrated municipal waste management [49].

In Malaysia, solid waste biodrying is still new and unknown to most people as opposed to other methods of solid waste treatment. This is because the solid waste pre-treatment technology has yet been realistically built in the country. The method is deemed to have great potential that must be highlighted by the stakeholders due to its benefits and contributions to various aspects of solid waste management, especially in environmental control and economic saving. In addition, combining biodrying with the existing solid waste treatment methods can also create an integrated and holistic solid waste management system.

Furthermore, biodrying can help to reduce the amount of solid waste delivered to landfills by recycling and converting it into materials that can benefit other sectors. This minimises various costs incurred by the government in solid waste management, especially the cost of operating landfills. Apart from its prominent advantages in recovery, this pre-treatment method can also address the recycling issue of municipal solid waste that has been mixed and wet. Thus, combining biodrying with materials recovery facilities (MRF) is deemed as a complementary initiative in integrated solid waste management.

7.7.1 Alternative Source of Energy

Nowadays, non-renewable sources of energy such as oil and coal continue to deplete. The current status of energy consumption suggests that the world will experience an energy shortage crisis for natural gas resources in the next 60 years, and the lifespan of coal can only last for another 130 years from now [66]. Therefore, there is an urgent need to explore the potential of alternative energy to compensate for the shortage of conventional non-renewable energy. This is mainly due to the fact that alternative energy (e.g. hydroelectric energy, solar energy, geothermal energy, biomass energy) is renewable, which guarantees its continuous existence. In this regard, municipal solid waste is categorised as one of the sources of biomass energy as it consists of organic matters from plants and animals [67]. It also contains biogenic materials such as papers, cardboards, foods, grass, leaves, woods, leather products and other flammable non-biomass materials such as plastics and synthetic materials made from petroleum [67].

Solid waste can be converted into renewable energy in the form of refuse-derived fuel (RDF) to replace the use of coals or fossil fuels in industries. Recently, fuel production has received significant attention particularly on the production of RDF, which has been proven to have extensive benefits [39]. Municipal solid waste can be treated using the biodrying method for the recovery and production of RDF [54]. Biodrying has been proven as a method that is capable of producing fuel with the least moisture content and high energy content [43]. The biodrying method is also capable of drying biomass while preserving and increasing its calorific energy [36]. The calorific value of Refuse Derived Fuel is 7000 cal/g, which is classified as brown coal [68]. Such a method of drying solid waste via natural metabolic can produce derivative fuel products to be used as alternative energy in various industries such as cement factories. Moreover, the end product of solid waste biodrying should be ground into small grain sizes for it to be used for RDF [37]. Therefore, solid waste biodrying has a significant prominence in the production of RDF, subsequently contributing towards the nation's profit-generating and economic development.

7.7.2 The Environment

Open or non-sanitary solid waste landfills have a negative impact on the environment as it contributes towards greenhouse gas emission and leachate pollution to underground water sources. For environmental benefits, biodrying needs to be done as a pre-treatment method that stabilises the organic matters in the wastes before it is disposed to landfills. Such a process will ensure that only matters that have been treated via the biodrying method are disposed to landfills while the remaining will be recycled. This helps to extend the lifespan of landfills and reduce the emission of greenhouse gases and leachate as the decomposition of organic matters has been reduced. Furthermore, the significant reduction of moisture content after the biodrying process allows the solid waste to be burned safely using incinerators without requiring extensive fuel consumption. This contributes to the preservation of the environment and improved environmental health as it minimises the release of toxic gases such as dioxins and furan caused by the burning of high-temperature waste. Solid waste dried using the biodrying method is also environmentally friendly when incinerated compared to wet solid waste [41].

Table 7.8 Comparison of the capital and operating costs between biodrying and rotary drying systems [42]

System/ item	Biodrying system		Rotary drying system	
	Investment (USD)	Operation percent maintenance	Investment (USD)	Installation percent maintenance (USD)
Plant	2,400,000	115,000		
Dryer			5,200,000	10,000,000
Furnace			350,000	500,000
Total			5,500,000	10,500,000
Grand total	2,515,000		16,000,000	

The use of biomass fuels such as RDF is environmentally friendly than fossil fuels because combustions involving biogenic fraction materials often produce neutral carbon that can reduce the total inventory of greenhouse gas emissions [59]. Subsequently, it realises the commitment made by the Malaysian Government during the 2009 United Nations Climate Change Conference (COP 15) in Copenhagen, where Malaysia agrees to reduce its carbon dioxide emissions by 40% in 2020 [69]. When compared to non-biodrying, the biodrying process can reduce CO_2 emissions by 13 times [68]. Another advantage of using RDF is that the sulphur content produced during its combustion is almost none as compared to 2%–4% sulphur dioxide in the combustion of fossil fuels, thus contributing to pollution [59]. These advantages, therefore, suggest that RDF produced from the biodrying method is beneficial and safe to be used as fuel and minimises environmental pollution.

7.7.3 *Cost Saving*

One of the important factors to consider in choosing a drying method is cost. Cost is among the influential factors to the outcome of good solid waste management [70]. Biodrying can benefit many parties, especially the government, by reducing operational and maintenance costs. The method uses an internal energy mechanism to dry the waste, unlike the conventional drying method, which requires expensive equipment and maintenance costs. Although the latter has the advantage of drying waste faster, the biodrying method has more perks in the economic and environmental perspective as it is more environmentally friendly and cost-effective. Table 7.8 shows the economic data related to the investments and operational costs of the biodrying and rotary drying systems for a capacity of 20,000 metric tonnes per annum.

The above data indicates that the investment cost to dry solid waste using the biodrying method is far more economical than the rotary drying system, where the cost incurred for the two drying methods is approximately 8 times in difference. In addition, the use of a rotary dryer system is less suitable in Malaysia as the local solid waste is high in moisture content, which reduces the combustion chamber

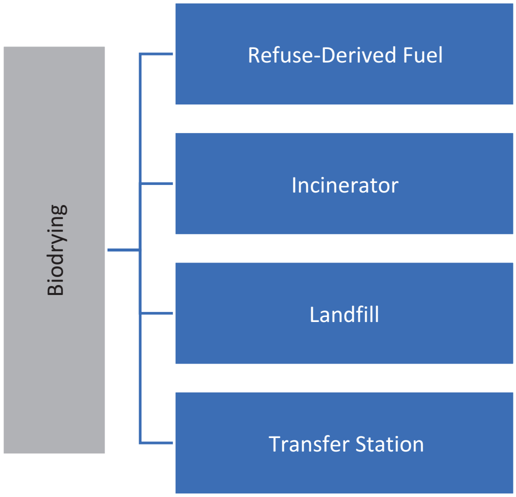


Fig. 7.35 Application of biodrying method in the solid waste management system in Malaysia

temperature as most of the thermal energy is used for evaporation. Such condition creates an incomplete combustion reaction and requires additional fuel to increase the temperature in the combustion chamber.

7.8 Potential Application of Biodrying

There is also a potential to combine biodrying with the existing solid waste treatment methods in Malaysia for its end product to generate profits to other treatment methods such as recycling, composting, as well as the energy and fuel industry. Drying of solid waste via biodrying is deemed to have a positive impact on the development of a solid waste management system in Malaysia. Figure 7.35 shows the end result of the biodrying method that can be applied for the subsequent process of solid waste management.

7.8.1 Refuse-Derived Fuel (RDF) Plant

Refuse-derived fuel plant, or RDF plant, is the first waste to energy (WtE) plant in Malaysia situated at the outskirts of Semenyih, Selangor. The pilot project began in 2006 through a collaboration between Kajang Municipal Council (MPKJ), Recycle Energy Sdn. Bhd. (RESB), Malaysian Nuclear Agency (Nuclear Malaysia) and Universiti Putra Malaysia (UPM). RDF is a green technology imported from India which comprises an intelligent mechanism capable of managing and treating between 700 and 1000 tonnes of waste per day. The technology can sort waste with combustible materials to be recycled into pellets known as RDF, which has the characteristics of high volatility, flammability and high calorific value due to its 20%–30% of moisture content.

The production of RDF from solid waste has contributed extensive benefits not only to the field of solid waste management but also to various industries such as cement and brick processing factories [8]. This is because the use of RDF as fuel is much cheaper than coal, which promotes significant savings to the operational costs. The conversion of waste to energy via the RDF technology has been proven by the establishment of a power generation plant in 2009 which uses RDF pellets as an alternative source of energy for the nearby locality. A joint venture was also signed with Tenaga Nasional Berhad (TNB) that enables the plant to supply 5.5 MW of electricity to the Malaysian giant utility company. Furthermore, useful materials such as plastics, glasses, bottles, metals and papers are made into valuable and sellable recycled materials. The advantage of this innovative system is that only 10% of the total amount of solid waste is disposed of at the landfills at the end of the process.

7.8.1.1 Limitations of the RDF Technology

Despite its advantages, the RDF technology has a number of limitations that are difficult to be addressed. The first RDF plant in Malaysia had to cease operation in April 2014 due to its incapability to process solid waste. As a result, a total of 30,000 tonnes of solid waste had to be transferred from the Semenyih RDF plant to the Tanjung Dua Belas Waste Landfill in Sepang. A site visit held at the RDF plant on 28 May 2014 had found no operations that took place at the plant. According to its Operation Officer, the plant's operation was temporarily shut at that time due to a technical problem involving the machinery, which was caused by the waste that was too wet. He further added that the high humidity of municipal solid waste, especially during the rainy season, serves as the main contributing factor that causes technical machinery failure, which has occurred since 2009. Among the common problems faced in the operation of this RDF plant are as follows:

1. Excessive ash content in the RDF causes the adhesion and accumulation of ash on the walls and clinker. This disrupts the operation of the boiler through issues such as heat transmission problems and decreases the boiler's efficiency.

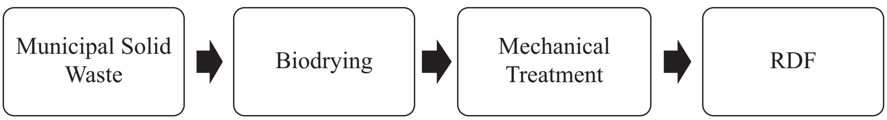


Fig. 7.36 Flowchart of combination of biodrying processes in RDF production

2. Incomplete RDF combustion before reaching the base of the ash system, which is caused by wet waste contents.
3. Excessive moisture content in the RDF calls the need for a compression process in its storage and causes RDF dropouts from the pneumatic carrier ducts and pipes.
4. The failure of air classification to remove large fractions of solid waste, which causes problems to the base of the ash system in the boiler.
5. Occurrence of wear and corrosion on mechanical equipment due to the abrasive nature of RDF ashes.
6. The pneumatic carrier system fails to deliver the required capacity without installation and other operational issues due to wear and tear.
7. Large textile patches are constantly stuck on mechanical equipment.

7.8.1.2 Application of Biodrying in the RDF Technology

The technical problems of the RDF operation thus suggest that the main inhibiting factor to the technology is the high content of moisture in solid waste. Such an issue often leads to a lack of efficiency and capacity in the boiler, thus resulting in incomplete RDF combustion. Therefore, biodrying is regarded as a suitable and practical method to be incorporated in RDF facilities as one of the preliminary processes in RDF production. This is because drying solid waste at the initial stage can facilitate the subsequent treatment processes such as sorting and segregation. Figure 7.36 shows a flowchart that illustrates the incorporation of biodrying into the process of RDF production.

The application of the solid waste biodrying method into the RDF technology can reduce the percentage of moisture content up to 20% and decrease the diffusion of carbon dioxide gas between 20% and 30% [49]. The main conditions in the production of RDF are high calorific value and the ease to be processed mechanically. This can be achieved through biodrying by lowering the residual moisture content and minimising the biodegradation process to stabilise the heat value of organic matter. Whereas the ease to be processed mechanically is achievable when the adhesion properties of the waste are reduced after it is dried.

7.8.2 Heat Treatment Plant (Incinerator)

A heat treatment plant, or incinerator, is a modern technology to convert waste into energy. This high-temperature waste incinerator plant has long been applied in developed countries such as Japan and Germany. Aligned with the rapid development of technology as well as Malaysia's desire to reach the status of a developed country, the selection of this technology has been given significant attention by the Government to set up more incinerators at selected locations across the country. However, such a proposal has become a controversial and sensitive issue that invites

Fig. 7.37 Solid waste was piled in the incinerator

a number of protests by the locals and various non-governmental organisations (NGOs) such as the Penang Consumers Association (CAP) and the Malaysian Socialist Party (PSM).

7.8.2.1 Limitations of the Incinerator Technology

Although the technology has been developed and applied in several locations, including Langkawi, Pangkor Island, Tioman Island and Cameron Highland, the extent of its effectiveness and efficiency is still doubted and debatable. The issue pertaining to the construction of four small-scale incinerator plants with a total cost of RM180 million has received major coverage from the mass media and prompted mixed reactions from the community due to the substandard physical performance of the project. Among the comments that describe the weaknesses of the incinerator project in Malaysia were reported in the Public Accounts Committee Report during the Thirteenth Parliament (2014) as follows:

1. The technology was built solely based on laboratory experiments and yet to be proven on a large-scale or real-world conditions.

Fig. 7.38 A malfunction waste sorting machine

2. The absence of actual data on emission and environmental control to guarantee that the incinerators can be maintained in compliance with the set emission standard.
3. The incinerator plant could not function autogenously throughout the longitudinal operation, and the temperature in the main chamber could not be sustained at the minimum operating temperature of 850 °C.
4. The incinerator plant failed to comply with the Environmental Impact Assessment (EIA) requirements to operate within the specified temperature range where it could only operate at 650 °C.
5. It failed to comply with a number of Detailed Environmental Impact Assessment (DEIA) requirements such as the installation of a continuous gas emission monitoring system (CEMS), leachate flows control system and toxic leakage characteristics (TCLP) testing procedure.
6. Most components, facilities and equipment were rusty, damaged and malfunctioned.

On 27 May 2015, a site visit was held at one of the incinerator plants located at Mukim Ulu Tenom, Blue Valley, Cameron Highland, Pahang. The 11-acre incinerator plant is capable of handling up to 40 tonnes of waste per day. According to the Technical Division Manager, the machinery and incinerating equipment at the plant had been experiencing frequent technical problems since its first operation on 31 December 2014. In fact, the plant had temporarily ceased its operation for almost a month prior to the site visit due to technical problems that stopped them from processing and treating the waste. This shows that the incinerator had only been operating for approximately 4 months since day 1. Among the factors that halted the incinerator plant to function properly were high moisture content that made the waste excessively wet, lack of skilled manpower to operate the machines and inefficacy in the management. Figures 7.37 and 7.38 illustrate the current condition of the Cameron Highlands incinerator plant taken during the site visit.

7.8.2.2 Application of Biodrying in the Incinerator Technology

Following the discussion above, a pragmatic solution that can be implemented to address these constraints is to introduce a treatment system that comprises a combination of several solid waste treatments. The purpose is to introduce a waste disposal system that combines both conventional treatment methods and advance technology known as the Integrated Solid Waste Management Concept (IWMS). It is believed that the incinerator technology can be successfully applied in Malaysia if it is combined with the biodrying method in order to dry the municipal solid waste before it is processed for waste incineration. This shall address the constraints related to high moisture content, thus diminishes the need for additional fuel during the combustion process. Furthermore, the increased caloric value of the waste materials as a result of biodrying can help to generate energy. The issue of toxic gas emissions such as dioxins and furan can also be avoided when the moisture content of municipal solid waste meets the standard required for this technology. In conclusion, the incinerator technology is more effective on the solid waste that has undergone the biodrying process.

7.8.3 Solid Waste Landfill

In the recent century, limitations in the aspect of space constraint as well as the negative impact on environmental pollution caused by the disposal of solid waste at landfills have placed it as the bottom hierarchy of the solid waste management system. Among the major issue that makes solid waste landfills less environmentally

Table 7.9 Typical parameter values of leachate [63]

Parameter (mg/L)	Acid phase	Intermediate phase	Methanogenic phase
pH	6.3–7.8	6.7–8.3	7–8.3
COD	950–40,000	700–28,000	460–8300
BOD_5	600–27,000	200–10,000	20–700
TOC	350–12,000	300–1500	150–1600
NH4-N	17–1650	17–1650	17–1650
TKN	250–2000	250–2000	250–2000

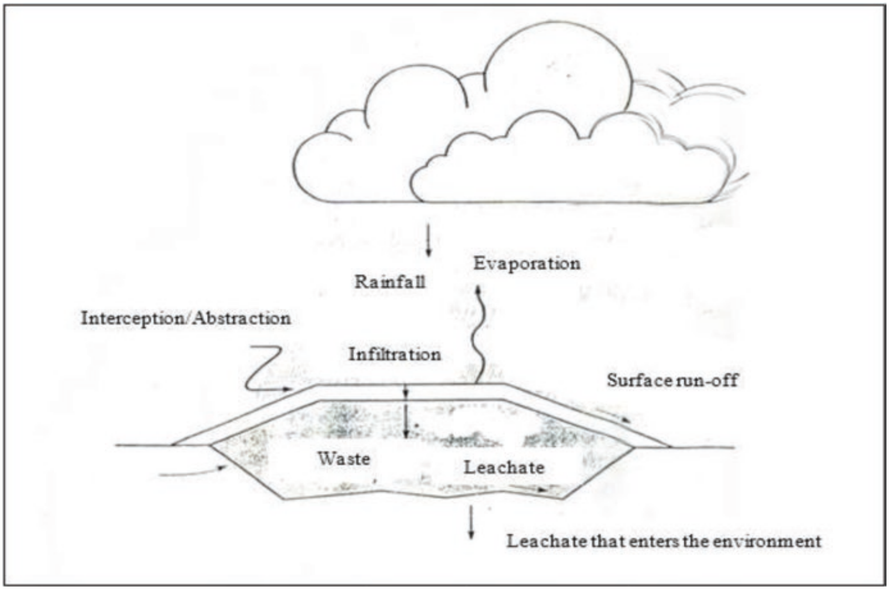


Fig. 7.39 The process of water balance and leachate production at landfills

friendly is the existence of leachate resulting from high liquid or water content in the waste dumps. This is because organic waste dumps that are buried in solid waste landfills still experience biodegradation activities over a long period of time, thus producing thick and toxic black liquid.

7.8.3.1 Limitations of Solid Waste Landfills

Leachate typically contains heavy metals, organic matters formed by various stages of decomposition and pollutants such as ammonia and sulphates. The toxic liquid is caused by the wet mixture of organic and other solid wastes, which then drains some of its chemical and biochemical constituents. Based on an interview held with the landfill's Operating Officer of Tanjung Dua Belas Sanitary Landfill, Kuala Langat, Selangor, the problem of excessive leachate has become a burden, particularly in terms of the operational and maintenance costs of the leachate treatment plant, which has to operate more intensively to treat the leachate. Although there are temporary daily landfills to control the production of leachate, the rapid generation of leachate due to higher waste intake still poses a problem to the landfill's management. Table 7.9 shows the typical parameter values of leachate.

Among the contributing factors that increase the rate of leachate generation are as follows:

1. High moisture content in the solid waste that can reach up to 60%–70%.

2. Tropical climate with high annual rainfall (i.e. an average rainfall of 2030 mm). The rainfall distribution in Malaysia is also uneven depending on wind gusts, cloud cover and topography.
3. Operational practices at the landfills, such as water surface control and the use of appropriate waste landfill covers.

Figure 7.39 shows the process of water balance and leachate production at landfills. The increasing quantity of leachate at landfills serves as an unhealthy sign for the environment. Therefore, having a proper leachate management system at every solid waste landfill is an important aspect that needs to be considered in the solid waste management system. This can be achieved by building a leachate treatment plant on every sanitary landfill as a control measure against such pollutants in the environment. In Malaysia, the construction design of a leachate treatment plant is based on the experience of treatment methods in tropical climate conditions, which consists of the biological treatment process and dissolved air flotation (DAF). Nevertheless, the operational and maintenance costs of the plant are excessively high compared to other functional costs of the waste landfill.

Fig. 7.40 Leachate spillage from a compactor truck

7.8.3.2 Application of Biodrying at Solid Waste Landfills

Based on the discussion, treating solid waste using the biodrying method before sending the residuals to landfills is therefore deemed as one of the best measures to control leachate and reduce the high cost of leachate water treatment. This is because solid waste that has undergone the biodrying process is stable and safe to be sent to a waste landfill. Furthermore, the method can also reduce greenhouse gas emissions at waste landfills that are caused by the anaerobic decomposition of waste. The lifespan duration of a landfill can also be extended if only bulk waste and non-recyclable municipal solid waste are sent there. Through the application of biodrying as a pre-treatment method to solid waste, the disposal of solid waste at landfills as the last option in the Malaysian solid waste management hierarchy can be realised.

7.8.4 Solid Waste Transfer Station

7.8.4.1 Limitations at Solid Waste Transfer Station

Leachate spillage on roads often occurs during the process of collecting and transferring solid waste from premises to either solid waste transfer stations or solid waste landfills. An audit inspection by the Department of Environment (DOE) has found that leachate was flowing on the road during the solid waste compression process. Moreover, it is also reported that cases of leachate spillage from compactor trucks are more prominent during the rainy season. Although most compactor trucks used by the local authority or privately owned are equipped with leachate reservoir tanks, the facilities are not well maintained as there are trucks with rusted and leaking tanks. Figure 7.40 shows leachate spillage from a compactor truck that causes the road to becoming dirty and polluted.

7.8.4.2 Application of Biodrying at Solid Waste Transfer Station

The problem of leachate spillage from compactor trucks during the process of collecting garbage from residential areas, business premises and institutions is difficult to control if the public is still unaware of the need to sort and separate their waste. Alternatively, it is also possible for the public to build a small-scale biodrying reactor at home to maintain a healthy ecosystem and show their support for environmental sustainability. For educational institutions such as colleges and universities, the availability of a small-scale biodrying plant shall create a sustainable zero waste environment within the campus. Applying the biodrying method at these premises will also protect the natural environment and reduce the problems of pollution and transmission of diseases, especially those involving leachate.

A solid waste transfer station is a facility where the waste will be transferred from a small collection vehicle such as a compactor truck to larger transportation to be sent to a solid waste landfill. A similar issue of leachate spillage will arise during the delivery of waste from the transfer station to the solid waste landfill. Therefore, adding a new facility to process and dry solid waste at the transfer station is believed to be a potential remedy to avoid leachate spillage and reduce the operational cost of the leachate treatment plant at the transfer station. On the other hand, drying is also utilised in the case of organic waste to increase hygienisation; nevertheless, the technique contributes to greater manufacturing costs [71].

7.9 Conclusion

The rapid pace of modernisation with the use of high technology that consumes a lot of external energy has resulted in many short- and long-term effects that harm and destroy life and the environment. The selection of technology in the treatment of solid waste should be studied and scrutinised in relation to the suitability of the waste's characteristics. Although developed countries have advanced and modern solid waste treatment technology, there is a growing trend in developed countries to preserve the concept of bio-engineering. This proves that using biological treatment methods is more advantageous in terms of environmental preservation, economic savings and the harmony of global ecosystem life. The addition of biodrying method as a preliminary treatment to other solid waste treatment technologies such as RDF plants, incinerators and solid waste transfer stations can have a positive impact on the solid waste management system, particularly in countries with high water content solid waste. The application of biodrying methods in solid waste management systems can have a significant impact, particularly in realising developing countries' aspirations for the construction of waste to energy plants to maximise the acquisition of resources and energy in the country.

Glossary

Biodrying Is a pre-treatment method for solid waste that combines biological and mechanical principles. It is a sort of natural biological solid waste treatment that uses internal heat to eliminate moisture. When compared to the use of high-cost, cutting-edge treatment technologies, natural biological treatment is an effective treatment method that is also environmentally friendly. Furthermore, biodrying waste can be used as an energy source. The potential for heat recovery from solid waste is facilitated and improved by biodrying of plants, which creates refuse-derived fuel (RDF) as the major product by eliminating excess moisture.

Calorific Value Is defined as the amount of heat produced by the complete combustion of a unit volume of a substance. Kilojoule per kilogram (kJ/kg) is the unit of calorific value. It is also known as a parameter used to define the energetic content of materials; it is also known as gross calorific value (GCV) or high heating value (HHV). It is significant because it provides the value of fuel or food in numbers that can be calculated using a formula. Because humans consume fuels and food on a daily basis, it is critical to track their consumption, which is also important in health and financial aspects.

Composting Is the natural process of microorganism 'rotting' or decomposing organic materials under controlled settings. After composting, raw organic materials such as crop residues, animal wastes, food waste, some municipal wastes, and suitable industrial wastes improve their suitability for application to the soil as a fertilising resource. Controlled biological decomposition of organic solid waste materials can occur under aerobic or anaerobic conditions. Composting can be accomplished in windrows, static piles and enclosed vessels.

Conduction Drying Is a method that heats the air using a heat source, such as an electric heater. Heat is transferred from the heater to the air through physical contact between the two. In an indirect heat-transfer dryer, wet materials are not in direct contact with heating media. A blower or fan is then used to convey the warm air to the drying area. The heat in the air is then used to speed up the drying process, which entails evaporating any water (or other liquid) that remains on the part after it has been cleaned and rinsed.

Convection Drying Is the use of convective transfer in the drying process. During convective drying, the ambient air is frequently heated. This air will circulate around the damp material. This contact between the heated air and the material results in a heat and mass exchange between the two media.

Dissolved Air Flotation (DAF) Has recently been understood as one of the most efficient and reliable methods for removing suspended solids (TSS), biochemical oxygen demand (BOD5), fats, oils and grease (FOG), phosphorus (P) and nutrients from wastewaters. Contaminants are eliminated by pumping air under pressure into a recycled stream of clarified DAF effluent to create a dissolved air-in-water solution. In an internal contact chamber, dissolved air escapes from the solution in the form of micron-sized bubbles that adhere to the contaminants, and this recycle stream is combined and mixed with incoming wastewater. Bubbles and contaminants rise to the surface and form a floating bed of material, which a surface skimmer removes into an internal hopper for further processing.

Dynamic Respiration Index Is used in a respirometer system to determine the current rate of aerobic microbial activity of solid recovered fuels. The current rate of aerobic microbial activity is determined by measuring the oxygen uptake rate by microorganisms to biodegrade easily degradable organic matter in the sample itself under defined continuous airflow and adiabatic conditions.

Freeze-Drying Is also known as lyophilisation is a water removal process that is commonly used to preserve perishable materials in order to extend their shelf life and/or prepare them for transport. Freeze-drying is the process of freezing a substance, then lowering the pressure and increasing the heat to allow the frozen water to vaporise (sublimate). The three steps of freeze-drying are freezing, primary drying (sublimation) and secondary drying (adsorption). Freeze drying can reduce drying times by up to 30%.

Green Technology Is the development and usage of products, equipment and systems that help to protect the natural environment and resources while minimising and reducing the negative effects of human activity. It can also refer to clean energy production, which is the use of alternative fuels and technologies that are less destructive to the environment than fossil fuels. Green technology's goal is to protect the environment, repair past environmental damage, conserve natural resources, and preserve the Earth's natural resources. Green technology has also grown into a thriving industry that is attracting massive amounts of investment capital.

Hydrolytic Literally means water reaction. It is a chemical mechanism in which a molecule is broken into two pieces by adding a molecule of water. The most common hydrolytic occurs when a salt containing a weak acid or a weak base (or both) is dissolved in water.

Perforated Baffle Is typically a straight pipe with a lot of small holes. As a result, vapour condensate can easily pass through this perforation.

Rotary Dryer Is used to remove excess water from organic materials in order to make them more usable. Rotary dryers elevate materials and circulate them through heated air, allowing moisture to evaporate and making organic materials viable. The feed materials in all rotary dryers pass through a spinning cylinder known as a drum. It is a cylindrical shell made of steel plates that is slightly inclined. In some circumstances, a negative internal pressure (vacuum) is used to prevent dust from escaping.

Solar Drying Is a system that makes use of solar energy to heat air and dry any substance that is loaded. Solar dryers can be classified as either direct or indirect. The former entails directly exposing the material to sunlight. In the latter, the material is dried by circulating hot air over it without being directly exposed to the sun. The benefits of any solar dryer would be determined by the type and amount of material to be dried.

Spray Drying Is one of the most energy-intensive drying methods; it is nevertheless necessary for the manufacturing of dairy and food product powders. Spray drying works by atomising the input liquid into small droplets, which are then subjected to a stream of hot air and converted into powder particles. Atomisation is a distinguishing feature of the spray drying process and is crucial in determining the finished product's quality. It involves creating a large number of droplets from a liquid stream, greatly increasing the liquid's surface area and allowing for a faster drying rate. A variety of simultaneous heat and mass transfer processes occur when the atomised droplets come into contact with the heated air currents entering the chamber. Heat is transferred to the product in order to evaporate moisture, and mass is transferred to the surrounding gas as a vapour.

Sun Drying Is the process to leave material outside in the sun and wind for approximately 7–10 days, depending on the temperature and humidity for good dehydration. In terms of drying temperature, the most important thing is to dry the material in bright, sunny and dry weather. The greatest part about sun drying is that it is a low-cost and low-investment process. However, there are a few drawbacks to sun drying; for example, the temperature cannot be controlled and may occasionally become overheated. Furthermore, sun drying is a labour-intensive method that involves a large number of people in the process. Furthermore, the sun drying process is slightly risky due to its reliance on the unpredictability of weather conditions.

The Bulking Agent Is a carbon-based substance that gives your compost pile structure (or bulk). Wood chips, wood shavings, sawdust, dry leaves, shredded landscape waste, shredded paper, shredded cardboard and animal bedding are all common examples. Inside the compost heap, a good bulking agent provides free air space. This traps air and oxygen, allowing the microorganisms in compost to work without having to introduce extra air on a frequent basis. A good bulking agent is a dry material that effectively balances the high moisture content of the food waste.

Thermophilic Bacteria Thrive at higher temperatures, while mesophilic bacteria thrive at lower temperatures. This means that thermophilic bacteria thrive at temperatures ranging from 45 to 122 °C, while mesophilic bacteria thrive at temperatures ranging from 20 to 45 °C. Mesophilic bacteria are thought to be the best soil decomposers. In addition, they contribute to food contamination and degradation. Thermophiles can be found in a variety of harsh environments, including direct sunlight-exposed soil, silage, compost heaps, volcanic environments, hot springs, deep-sea hydrothermal vents and so on. Thermophiles include archaea and bacteria. These organisms have strong structures that can withstand high temperatures.

Waste Is defined as any substance that is discarded after its primary use or that is worthless, defective and useless. The primary aim of waste management is to reduce the harmful effects of hazardous waste on the environment and human health. If waste is harmful or toxic, it could potentially be a source of disease and death, not just for humans, but for everything that supports life, such as water, air, soil and food.

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Chapter 8
Landfill Leachate Treatment

Hamidi Abdul Aziz, Mohamed Shahrir Mohamed Zahari, Zaber Ahmed, Shahrul Ismail, Izan Jaafar, Mohd Suffian Yusoff, Lawrence K. Wang, and Mu-Hao Sung Wang

Abstract Disposal of municipal solid waste is an environmental burden worldwide, and landfilling is still the widely applied solution for the management of discarded solid waste because of its cost-effectiveness and simpler operational mechanism. Due to the complex reactions inside, landfills generate severely polluted wastewater streams recognized as leachate. Leachate is concentrated wastewater with extreme pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), organic refractory compounds, inorganic salts and toxicity. It is a typical dilemma of a landfill system and a potential threat for environmental elements, which must be treated before discharge into water bodies. Because of the variability in waste composition depending on the landfilling practice, local climatic conditions, landfill's physicochemical conditions, bio geochemistry and landfill age, treatment of leachate becomes more critical than municipal wastewater.

H. A. Aziz (✉)
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Mibong Tebal, Pulau Pinang, Malaysia

Solid Waste Management Cluster, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: cehamidi@usm.my

M. S. M. Zahari · S. Ismail
Faculty of Ocean Engineering, Technology and Informatics, Universiti Terengganu Malaysia, Kuala Terengganu, Terengganu, Malaysia
e-mail: shahrir@umt.edu.my; shahrul.ismail@umt.edu.my

Z. Ahmed · M. S. Yusoff
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Mibong Tebal, Pulau Pinang, Malaysia
e-mail: suffian@usm.my

I. Jaafar
Faculty of Science and Marine Environment, Universiti Terengganu Malaysia, Kuala Terengganu, Terengganu, Malaysia
e-mail: izanjaafar@umt.edu.my

L. K. Wang · M.-H. S. Wang
Lenox Institute of Water Technology, Latham, NY, USA

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Numerous biological, physicochemical treatment methods are being practised worldwide for landfill leachate. This chapter aims to summarize an overview of the different innovative options applied for landfill leachate treatment and the way forward.

Keywords Biological treatment · Chemical treatment · Municipal solid waste · Physical treatment · Semi-aerobic landfill · Leachate

Nomenclature

AF	Anaerobic filter
$AlSO_4$	Aluminium sulphate
AOP	Advanced oxidation process
AOX	Halogenated hydrocarbon
ASBR	Anaerobic sequencing batch reactor
ASEAN	Association of Southeast Asian Nations
BOD	Biochemical oxygen demand
BOD_5	5 Days biochemical oxygen demand
$CaCO_3$	Calcium carbonate
$CaH_2PO_4.H_2O$	Calcium hydrogen phosphate
CBOD	Carbonaceous biochemical oxygen demand
CEC	Cation exchange capacity
Cl^-	Chloride
C/N	Carbon to nitrogen ratio
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COPTS	Cross-linked oil palm trunk starch
DAF	Dissolved air flotation
DNA	Deoxyribonucleic acid
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
EF	Electro-flotation
FBR	Fluidized bed reactor
$FeCl_3$	Ferric chloride
$FeSO_4$	Ferrous sulphate
GAC	Granular activated carbon
H_2	Hydrogen
H_2O	Water
H_2O_2	Hydrogen peroxide
H_2SO_4	Sulphuric acid

H_3PO_4	Phosphate acid
HCl	Hydrochloric acid
HRT	Hydraulic retention time
IAF	Induced air flotation
JSS	Jackfruit seed starch
LMC	Larger molecular weight
MAP	Magnesium ammonium phosphate
MBBR	Moving bed biofilm reactor
MBR	Membrane biological reactor
MF	Microfiltration
$MgCl_2.6H_2O$	Magnesium chloride
MgO	Magnesium oxide
$Mg\ (OH)_2$	Magnesium hydroxide
$MgSO_4$	Magnesium sulphate
MOC	Mean oxidation number of carbons
MSW	Municipal solid waste
MW	Molecular weight
$Na_2HPO_4.12H_2O$	Sodium hydrogen phosphate
NaCl	Sodium chloride
NaOH	Sodium hydroxide
NF	Nanofiltration
NH_3	Ammonia
NH_4^+	Ammonium
NH_4–N	Ammoniacal nitrogen
NH_4OH	Ammonium hydroxide
NO_3-N	Nitrite
NOM	Natural organic matter
NSTS	Native sago trunk starch
O^3	Ozone
OCl^-	Hypochlorite ions
OH^-	Hydroxide ion
OPTS	Oil palm trunk starch
PAC	Powdered activated carbon
PO_3^{4-}-P	Orthophosphate
PtCo	Platinum cobalt
RBC	Rotating biological contactor
RF	Rice flour
RO	Reverse osmosis
SALL	Semi-aerobic landfill leachate
SBR	Sequencing batch reactor
SiO_2	Silicon dioxide
S-MBR	Activated sludge plant equipped with filtration membrane
SO_4^{2-}	Sulphate
THM	Trihalomethanes
TiO	Titanium oxide

TL	Tobacco leaf
TN	Total nitrogen
TOC	Total organic carbon
TSS	Total suspended solid
UASB	Up-flow anaerobic sludge blanket
UF	Ultrafiltration
UV	Ultraviolet
VFA	Volatile fatty acid
VOC	Volatile organic carbon
VS	Volatile solid

List of Symbols

Δ ED	is the variation of water content in waste
b	is the adsorption energy
B	is the quantity of water produced by biochemical reactions
C_0	is the initial concentration of adsorbate (mg/L)
C_b	is the breakthrough leachate concentration (mg/L)
C_e	is the equilibrium concentration of the remaining substrate in the water (mg/L)
C_i	is the influent leachate concentration (mg/L)
ED	is the water content of the waste
ETR	is the real evapo-transpiration
G	is the water loss as vapour associated with biogas
I	is the infiltration at the bottom of the cell
k	is the constant
K_1	is the equilibrium rate constants of pseudo first order (min^{-1})
K_2	is the equilibrium rate constants of pseudo-second order (g/mg min)
K_f	is the Freundlich affinity coefficient (L/mg)
L	is the leachate volume that can be produced
M	is the mass of the adsorbent
M_c	is mass of adsorbent (limestone) (g)
n	is the exponential constant, which represents the adsorption capacity
P	is the rainfall amount of the site
Q	is the flow rate (m^3/day)
q	is the maximum adsorption capacity (mg/gm) to complete monolayer
q_e	is the amount of the pollutant adsorbed (mg/g) at equilibrium
q_t	is the amount of the pollutant adsorbed (mg/g) at time t
R_{ext}	is the water quantity dripping from outside the site inward
R_{int}	is water dripping from the inside to the outside of the site
RM	is the Ringgit Malaysia currency

tb	is time to breakthrough (day)
V	is the volume of sample (ml)
X	is the mass of the adsorbate
$(x/m)_b$	is field breakthrough adsorption capacity (g/g)

8.1 Introduction

In many parts of the world, the disposal of municipal solid waste (MSW) has become a major environmental issue. Researchers have projected that the generation of MSW will keep rising up to 16.76 million tons per year in 2020. An excessive amount of MSW does not only create a burden on the disposal method, but hazardous wastes produced from the disposal site will also give major problems to cope especially towards our environment and human health.

The most common method of disposing of solid waste is to use a sanitary landfill due to its cost-effectiveness. In this method, MSW is dumped on the ground and covered up with a few layers of soil. Even though this method is cost-effective and simple to use, it generates a by-product called leachate that is difficult to remediate because of the mixture and compression of different types of MSW.

Leachate contains high concentrations of biodegradable and non-biodegradable products, such as organic matter, phenols, ammonia nitrogen, phosphate, heavy metals, and sulphur dioxide, in addition to its strong colour and foul odour. Leachate that is discharged into the environment without extensive treatment can cause a wide range of acute environmental and human health issues.

8.2 Types of Landfill

Conventional landfilling is a method that uses several layers of soil to cover and compact the MSW. Landfill sites can be classified into five categories such as anaerobic landfill, anaerobic sanitary landfill, improved anaerobic landfill, semi-aerobic landfill, and aerobic landfill. However, the most common landfills are anaerobic, semi-aerobic landfill, and aerobic.

In an anaerobic landfill (Fig. 8.1), solid waste is dumped into a dug area or valley, and water is merged to allow for an anaerobic process to take place. This basic landfill has caused many serious environmental and human health problems by producing hazardous by-product leachate.

In a semi-aerobic landfill (Fukuoka method) (Figs. 8.2 and 8.3) [1], O_2 is supplied spontaneously by the collection pipe to stabilize the solid waste. Therefore, the collection pipe is designed to be bigger than the previous model, so it can function to collect leachate and provide O_2. The aerobic process occurs here, thus increasing the decomposition rate of solid waste.

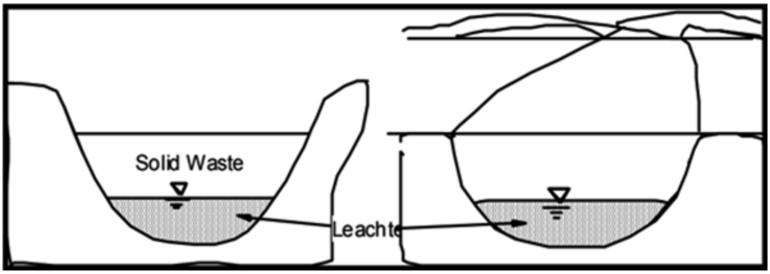


Fig. 8.1 Anaerobic landfill

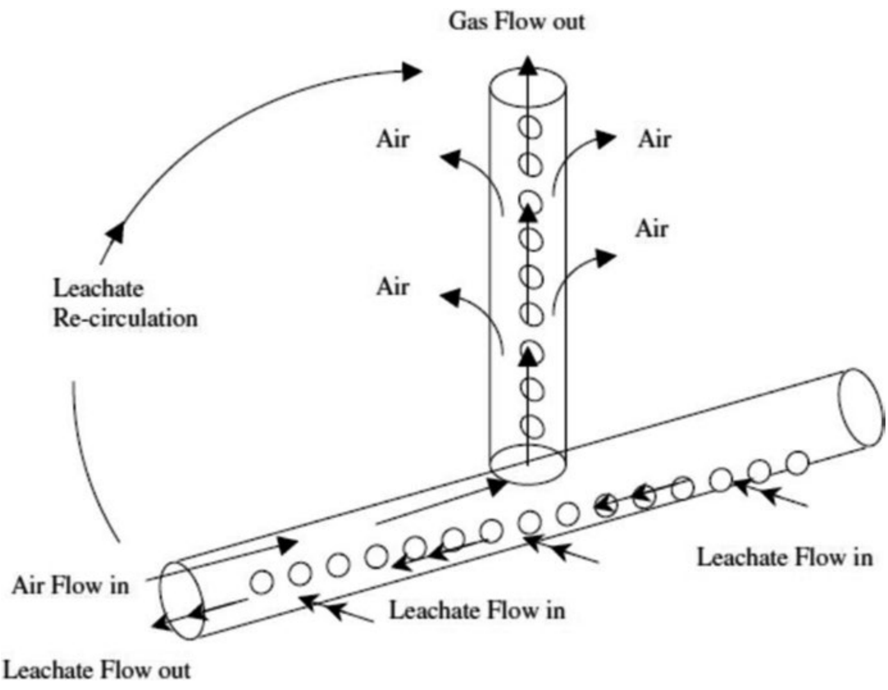


Fig. 8.2 Concepts used in Fukuoka method (semi-aerobic system) [1]

In aerobic landfill (Fig. 8.4), it is designed to enhance the aerobic process in landfill system since semi-aerobic landfill has performed well in the biodegradation and stabilization of landfill. Air and re-circulation leachate systems are also installed in order to increase and maintain the humidity as well as to supply nutrients for the microorganisms present in the water sample.

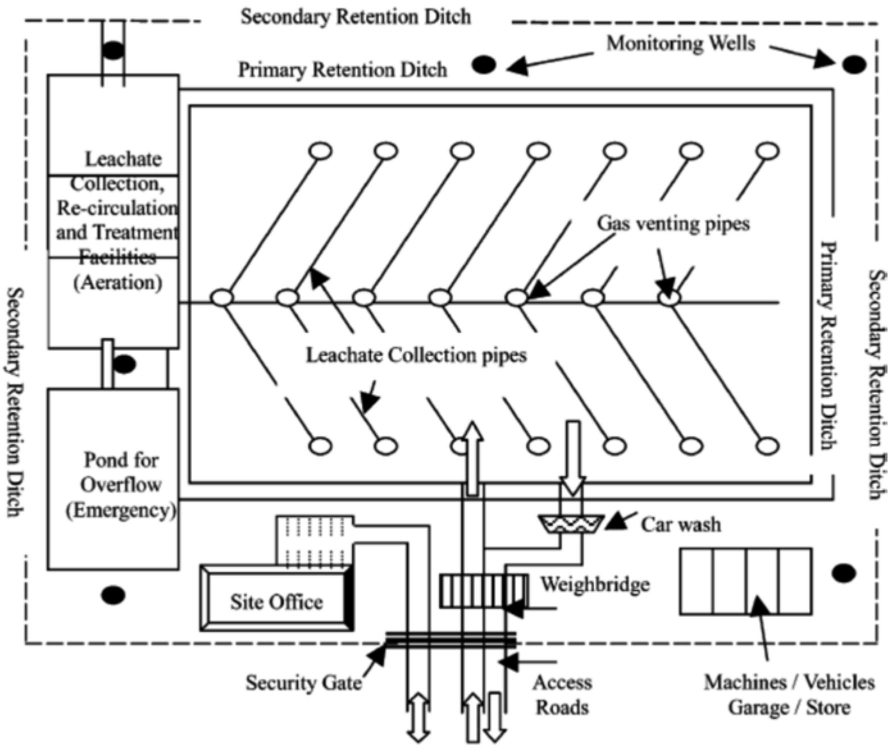


Fig. 8.3 Semi-aerobic landfill site conceptual diagram shown in plan view [1]

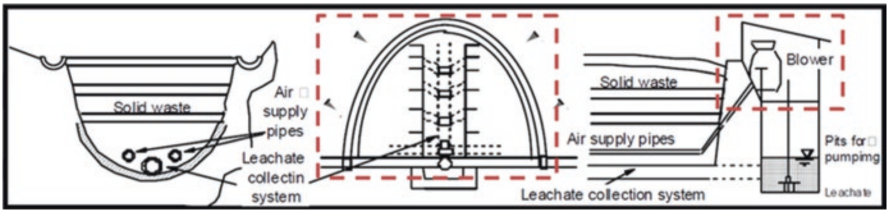


Fig. 8.4 Aerobic landfill

8.3 Formation of Landfill Leachate and Its Composition

8.3.1 Leachate Formation

Higher loading of municipal solid waste, which has a complex chemical composition [2], local climatic conditions, landfill physicochemical conditions, and seasonally varying volume [3] all of these factors make leachate treatment more difficult and complicated than municipal sewage or industrial effluent [4]. Over the last few decades, there has been a lot of interest in the novel and upgraded landfill leachate treatment systems for greater pollutant removal. The applicability, variability, efficiency, and economic value of landfill leachate treatment are mostly determined by the landfill's type and construction, age, and leachate properties [5]. Managing leachate, the water that seeps through the waste, is one of the most important aspects of landfill design, operation, and maintenance.

There are a lot of leachates in a landfill because rainwater seeps into the garbage and removes pollutants into the water phase. In addition to factors such as waste content, moisture and oxygen availability, and the hydrology of the site, factors such as landfill design and operation and the landfill age also influence leachate composition. Even heavy metals can be found in municipal solid waste leachate because of the wide range of organic and inorganic elements present. It contains organic breakdown products and soluble ions, which, if not properly treated, could pollute surface and ground waterways. BOD, COD, nitrogen, and heavy metals are typically high in leachates. As a result, adequate knowledge of landfill leachate properties is required in order to select the optimal treatment approach using biological, physical, or physicochemical methods [6].

Commonly, landfill leachate is categorized into two phases based on landfill duration, i.e. young leachate as well as matured or stabilized leachate. The 'young' acidogenic phase leachate contains a large amount of organic matter that is easily degraded. Soluble acids such as free volatile fatty acids (VFAs), amino acids, other low molecular weight compounds, and gases like H_2 and CO_2 are formed as a result of this anaerobic fermentation reaction. VFA concentrations can be quite high, accounting for up to 95% of TOC, resulting in low pH (around 4). COD levels typically range from 3000 to 60,000 mg/L. The presence of considerable volumes of biodegradable organic matter is indicated by high BOD_5/COD values of 0.5–0.8 (as shown in Table 8.1). Low pH and VFA interactions make iron, zinc, and nickel more soluble, which results in higher concentrations of these metals in this phase.

The reduced content of VFAs in mature leachate from the methanogenic phase is one of the characteristics of this phase. This is because the gaseous end products of the second fermentation cycle are CH_4 and CO_2. Humic and fulvic acid-like substances begin to take over the organic matter in the leachate as the amount of VFAs and other quickly biodegradable organic compounds in the leachate decreases. As a result, stabilized leachates have a low BOD_5/COD ratio, which is usually about 0.1. Humic compounds give stabilized leachates a dark colour. In matured leachate, a decrease in VFAs leads to a higher pH. Stabilized leachates have the same pH of about 8. The concentration of heavy metal ions is frequently low [7] due to the decreasing solubility of many metal ions.

Aziz et al. [9–14] have measured leachate quality at different landfills in Malaysia (Ampang Jajar Landfill Site, APLS; Alor Pongsu Landfill Site, APLS; and Pulau Burung Landfill Site, PBLS). The Alor Pongsu Landfill Site (APLS) is an open dumping site that has been in operation since the year 2000. The landfill is located at 5° 05′ 14.20″ N and 100° 36′ 10.53″ E in Bagan Serai, Perak, Malaysia. It is classified as an anaerobic, old, and matured landfill, and the leachate has been stabilized for more than 20 years. Typically, it receives 660,000 metric tons of solid waste per year, which equates to an average of 200 metric tons of household waste per day. There were 14 samples of leachate from the leachate pond (Fig. 8.5) taken from November 2018 to April 2021. Table 8.2 shows the results of the experiment.

Table 8.1 Typical leachate characteristics based on their age [8]

Parameters	Young leachate	Matured leachate
pH	4.0–5.5	7.5–9.5
BOD_5 (mg/L)	10,000–30,000	200–300
COD (mg/L)	20,000–60,000	2000–2500
TOC (mg/L)	1500–20,000	100–400
NH_3-N (mg/L)	10–800	20–900
Organic nitrogen (mg/L)	10–800	80–120
Nitrate (mg/L)	5–40	5–10
Total suspended solids (mg/L)	200–2000	150–450
Iron (mg/L)	50–1000	30–200
Potassium (mg/L)	200–800	50–400
Sulphate (mg/L)	100–1000	30–50
Chloride (mg/L)	1000–3000	100–400
Heavy metals (mg/L)	>2.0	<2.0
Phosphate (mg/L)	20–70	4–8
Total hardness (mg/L)	300–10,000	200–500
Biodegradability	High	Low
Organic compounds	80% volatile fat acids (VFA)	Humic and fulvic acids

Fig. 8.5 Leachate pond at APLS

Table 8.2 Leachate Characteristics APLS [9, 14]

Parameters	Unit	Min	Max	Mean	Discharge limit[a]
Temperature	°C	26.48	31.72	29.10	40
Dissolved oxygen	%	0.70	16.70	8.70	–
Dissolved oxygen	mg/L	0.04	4.38	2.21	–
Conductivity	μs/cm	13,720	18,149	15,934	–
Total dissolved solid	mg/L	8480	10,860	9670	–
Salinity	ppt	7.47	9.39	8.43	–
pH	–	7.47	8.76	8.12	6.0–9.0
Suspended solid	mg/L	395	699	547	50
Turbidity	NTU	16	338	306	–
Colour	Pt-Co	16,389	23,020	19,705	100
Ammoniacal nitrogen	mg/L	870	1850	1360	5
COD	mg/L	3080	5323	4202	400
BOD_5	mg/L	28	333	181	20
BOD_5/COD ratio		0.01	0.08	0.05	–
Zeta potential	(mV)	−24.80	−21.60	−23.20	–
Chromium (Cr)	mg/L	0.04	0.26	0.15	0.2
Iron (Fe)	mg/L	4.01	10.91	7.46	5
Manganese (Mn)	mg/L	0.10	1.38	0.74	0.2
Zinc (Zn)	mg/L	0.20	1.04	0.62	2

[a] Discharge leachate limits by the Environmental Quality Act (EQA) (Control of Pollution from Solid Waste Transfer Section and Landfill) Regulations 2009 (PU (A) 433) Regulation 13

Ampang Jajar Landfill Site (AJLS) was designed semi-aerobically, in contrast to Alor Pongsu Landfill Site (APLS), which was based on the Fukuoka Method. Perforated pipes embedded in graded boulders are used to collect leachate in leachate collection ponds. Leachate from this method contains fewer organic contaminants than leachate from AJLS, which received both domestic and industrial wastes during operation. The AJLS site disposal operation was ceased in 2001, and the waste disposal has been shifted to a new site (Pulau Burung Landfill Site, PBLS). The leachate compositions sampled from the leachate pond (Fig. 8.6) between the years 2009 and 2012 are presented in Table 8.3.

Meanwhile, Pulau Burung Landfill Site (PBLS) is situated near the Byram forest reserve at latitude 5° 12′ 24″ N and 100° 26′ 24″ E longitude, about 8 km from the city of Nibong Tebal, Pulau Pinang, Malaysia. The overall 62.4 ha area is occupied with landfill, and the remaining area of about 33 ha is presently operational, with approximately 2000 tons/day MSW being disposed of in this landfill site. PBLS is located next to the coastlines (200 m) and receives high salinity water with the surrounding natural liner of marine clay. In the year 2001, this landfill had been promoted to sanitary landfill (level III) (semi-aerobic system) compared to when it first operated in year 1980s (open dumping/control tipping). From 2013, the site turned to an anaerobic system. The characteristics of the baseline level from PBLS were examined and monitored for a 12-month duration. The investigation started from

Fig. 8.6 Ampang Jajar Landfill Site Leachate Collection Pond, Penang, Malaysia

Table 8.3 The Ampang Jajar landfill site's leachate parameter (AJLS) (2009–2012) [11, 12]

Parameter	Range	Average	Standard discharge limit[a]
pH	8.33–8.52	8.44	5.5–9
Turbidity (NTU)	23.3–103	56.5	–
Colour (Pt-Co)	260–686	429	100 ADMI
Suspended solids (mg/L)	33–240	146	100
BOD_5 (mg/L)	48–101	86	50
COD (mg/L)	500–710	632	100
BOD_5/COD	0.10–0.14	0.14	
Ammoniacal-N (mg/L)	200–602	397	–

[a] Standard discharge limit of landfill leachate, Control of Pollution From Solid Waste Transfer Station and landfill, Regulation 2009, under the Malaysian Environmental Quality Act 1974 [15]

January until December 2019 with a total of 24 sample batches. Figure 8.7 shows the leachate retention pond, where the samples were taken. The results are shown in Table 8.4.

More than one-third of the leachate components were found to have exceeded their permitted discharge limit in Tables 8.2, 8.3, and 8.4. Based on the landfill's alkaline pH, it is in a mature state. To classify a landfill leachate, the biodegradability ratios (BOD_5/COD) ranging from 0.01 to 0.5 are commonly used. The younger the leachate, the lower the BOD_5/COD ratio. Due to its low biodegradability, the leachate is considered stable with a BOD_5/COD ratio of less than 0.1. Stabilized and old leachate ($BOD_5/COD < 0.1$) can be identified in the APLS and AJLS samples, while moderate leachate ($BOD_5/COD < 0.1$) can be identified in the PLBS sample (mixture of old and fresh leachate). While initially operating as an anaerobic landfill (from 2001 to 2013), PBLS was initially operated as a semi-aerobic landfill.

Fig. 8.7 The leachate collection pond at the Pulau Burung landfill site (PLBS), Penang, Malaysia

8.4 Leachate Quantity

8.4.1 Introduction

Several factors influence the volume of landfill leachate produced and the extraction of potential pollutants from waste, including solid waste composition, degree of compaction, waste absorptive capacity, waste age, seasonal weather variations, precipitation levels, landfill temperature, size, hydrogeological conditions in the vicinity of the landfill site, landfill engineering and operational factors, pH, landfill chemical and biological chemistry, and landfill engineering and operational factors. [9].

Leachate generation rates are determined by the amount of liquid in the waste at the time of disposal and the amount of precipitation that enters the landfill through infiltration or falls directly on the waste. The biological decomposition of biodegradable organic components, chemical oxidation processes, and the chemical composition of leachate will change as the landfill decomposes will all influence the chemical composition of leachate. These contaminants must be eliminated to avoid pollution to receiving water (surface and groundwater). Because of the high concentration and variety of contaminants, a combination of biological, physical-chemical,

Table 8.4 Pulau Burung landfill site's leachate parameter as of 2019 [10, 11, 13]

No.	Parameter	Unit	January to December 2019		Standard discharge limit[a]
			Range	Average	
1	Temperature	(°C)	29.40–31.90	30.30 ± 1	40
2	Ammoniacal nitrogen (NH_3-N)	(mg/L)	3159–3987	3889 ± 169	5
3	Colour	(Pt-Co)	4930–18,380	8240 ± 261	100
4	Salinity	(ppt)	15.62–18.83	17.53 ± 1.10	–
5	Conductivity	(µs/cm)	25,111–34,121	31,285 ± 2026	–
6	Resistivity	(Ω/cm)	32.31–39.82	32.11 ± 2	–
7	Suspended solid (SS)	(mg/L)	473–2021	942 ± 539	50
8	Turbidity	(NTU)	92–251	157 ± 43	–
9	pH		7.99–8.19	8.17 ± 0.04	6–9
10	Biological oxygen demand (BOD_5)	(mg/L)	213–435	316 ± 69	20
11	Chemical oxygen demand (COD)	(mg/L)	4201–6648	5120 ± 887	400
12	Total dissolved solid (TDS)	(mg/L)	20,088–27,297	25,028 ± 1620	–
13	Dissolve oxygen (DO)	(mg/L)	1.10–1.82	1.36 ± 0.23	–
14	Aluminium (Al)	(mg/L)	1.91–3.21	2.34 ± 0.41	–
15	BOD_5/COD	–	0.05–0.07	0.06 ± 0.01	–

[a] Standard discharge limit of landfill leachate, Control of Pollution from Solid Waste Transfer Station and landfill, Regulation 2009, under the Malaysian Environmental Quality Act 1974 [15]

and chemical treatments is always necessary. The effectiveness of leachate treatment systems is also influenced by a number of parameters, including the composition and concentration of the leachate, its volume, the age of the landfill, and the types of landfills. There are a few factors that influence the leachate quantity, such as the waste compositions, landfill maturity, climate, and many more, as described in detail below.

8.4.1.1 Composition of Wastes

In general, heterogeneity of the composition of solid waste has a strong influential impact on leachate quality as the biological activities within the landfill sites mostly correlated with its composition [10]. The waste from domestic sources (rubbish, food, garden wastes) or agricultural and animal residues in most cases contribute to the organic matter in leachate, while hospital waste or construction and demolition debris are responsible for inorganics [11]. The majority of contaminants in leachate come from disposed waste, which breaks down and releases pollutants into the water. The physical properties of waste, i.e. size, density, moisture content, also influence the leachate strength, quality and flow rate etc. [12].

8.4.1.2 Maturity of Landfill

Throughout the landfill operation, the age of the landfill becomes a key factor in determining the waste composition and leachate quality [13]. Since the biochemical decomposition of waste is associated with landfill maturity, it also influences the leachate quality. Most commonly, leachate from a young landfill is highly biodegradable and contains high BOD, COD while declining the values with time in matured landfill leachate [14]. Because as a landfill ages, the waste becomes more stable, and the toxins in leachate gradually fade away. It transitions from the acclimation phase to the maturation phase. Leachate characteristics change at each stage of biochemical decomposition [15].

8.4.1.3 Climatic Impact on Landfill

Climate parameters such as rainfall, temperature, humidity, or moisture content, as well as seasonal climatic fluctuations, have a significant impact on microbial activity in landfills and, as a result, waste biodegradation efficiency [16]. Biodegradation is slower during the dry season and improves during the wet season. Quantification of landfill leachate is commonly approximated using water balance principles by estimating the volumes of water seeping into the landfill from precipitation and subtracting the amounts of water consumed [17]. Because higher temperatures increase bacterial activity for biochemical waste breakdown, biological decomposition appears to be faster at higher temperatures [18].

8.4.1.4 Waste Degradation Mechanism Inside the Landfill

The waste processing mechanism inside the landfill can have a significant impact on leachate properties. During the early stages of waste stabilization, leachate from mechanically reduced or shredded waste is significantly polluted, but leachate from unshredded waste is less polluted. In general, increased surface area and, as a result, increased rates of biodegradation in shredded waste landfills can be linked to higher strength leachate. Waste processing is also linked to landfill systems (aerobic, anaerobic, and semi-aerobic), all of which have an impact on leachate quality [19]. Semi-aerobic leachate is frequently connected with the recirculation of leachate. This is referred to as Fukuoka method. It has become a preferred option in a few countries, such as Malaysia. This method encourages aerobic waste decomposition and allows for early waste stabilization, which reduces the production of methane and other greenhouse gases. Also, the landfill settlement is faster due to the rapid waste biodegradation process. The leachate collection pipe and vertical gas vent are connected and open to the air on both the ends in this type of landfill to maximize the heat generated by organic decomposition, resulting in a temperature difference between the landfill and the surrounding environment (natural convection). Natural external air flows naturally through convection from the leachate collection pipe's end, requiring no external energy. As a result of the air movement, the aerobic zone extends into the waste layer, speeding up organic breakdown and reducing the time it takes for waste to stabilize. The quality of the leachate is also affected by the entire process [20], where the concentration of leachate in semi-aerobic landfills is usually lower than in aerobic landfills.

8.4.1.5 Quantification of Leachate Quantity

It's also crucial to determine the generation rate of leachate before deciding on the treatment option. Several models can be used to predict the annual leachate volume. Software is also used for leachate volume calculation, but generally, they do not provide universal solutions to the current difficulties encountered in developing countries. The basic equation of water balancing for leachate volume calculation is as shown in Eq. (8.1), assuming an effective sealing to nearly 100%, infiltration and runoff would be zero [9]:

$$\mathrm{L = P + ED + B - G - I - ETR + R_{ext} - R_{int} \pm \Delta ED} \tag{8.1}$$

where L the leachate volume that can be produced, P the rainfall amount of site, ETR the real evapo-transpiration, ED the water content of the waste, I the infiltration at the bottom of the cell, R_{ext} the water quantity dripping from outside the site inward, R_{int} water dripping from the inside to the outside of the site, Δ ED the variation of water content in waste, B the quantity of water produced by biochemical reactions, and G the water loss as vapour associated with biogas.

However, estimation based on the actual on-site data has not been widely reported. A study was conducted at two semi-aerobic sanitary landfill sites in Malaysia, namely Ampang Jajar Landfill Site (AJLS) and Pulau Burung Landfill Site (PBLS) in Pulau Pinang, to measure the real amount of leachate generation in the field from different ages of landfill [21]. The site was set up with a variable number of lifts (layers), each measuring 5 m in height. SALL4 (Semi Aerobic Landfill Leachate 4) was discovered for a 4-year-old landfill, and SALL10 (Semi Aerobic Landfill Leachate 10) was discovered for a 10-year-old landfill, as shown in Eqs. (8.2) and (8.3). The equations can be used to design a leachate treatment plant in Malaysia as a general guide. These parameters are crucial for future landfill design, especially for the construction of leachate pipes, collection systems, retention ponds, and treatment facilities.

The maximum leachate generation rate for a 4-year-old landfill was discovered to be around 8 m^3 $lift^{-1}$ ha^{-1} day^{-1}, which was given the name SALL4. The leachate generation rate for a 10-year-old landfill was about 4.2 m^3 $lift^{-1}$ ha^{-1} day^{-1}, and it was dubbed SALL10 [21]. These parameters are crucial for future landfill design in Malaysia, especially for the construction of leachate pipes, collection systems, retention ponds, and treatment facilities. This chapter discusses the treatability of leachate from the Pulau Burung Landfill Site (PLBS) and the Ampang Jajar Landfill Site (AJLS) in Penang, Malaysia. In 2001, AJLS ceased operations and was declared closed.

For new site (less than 4 years):

$$\text{Flowrates}, Q = 8\,\text{m}^3 / \text{day} \quad \text{ha} \quad \text{lift} \tag{8.2}$$

For old site (more than 8 years):

$$\text{Flowrates}, Q = 3\,\text{m}^3 / \text{day} \quad \text{ha} \quad \text{lift} \tag{8.3}$$

Example:

A semi-aerobic landfill in Malaysia has the following characteristics.

Age of landfill = 3 years

Amount of waste disposed of = 2500 tons/day

The amount of daily cover is estimated to be around 30% of the total volume

Compacted density = 400 kg/m^3

Number of lifts = 3 (depth of each lift 5 m)

Calculate the amount of leachate of this landfill in m^3/day.

Solution:

Compute the area of landfill:

$$\text{Compacted density} = \text{mass} / \text{volume}$$
$$400\,\text{kg} / \text{m}^3 = (1000 \times 1000\,\text{kg} / \text{volume})$$
$$\text{Volume of waste} = 2500\,\text{m}^3 / \text{day}$$
$$= 2{,}737{,}500\,\text{m}^3 \text{for 3 years}$$

$$\text{Volume of daily cover} = 0.3 \times 2{,}737{,}500\,\text{m}^3$$
$$= 821{,}250\,\text{m}^3$$
$$\text{Total volume} = 3{,}558{,}750\,\text{m}^3$$

$$\text{Number of lifts} = 3$$
$$\text{Total height of lift} = 3 \times 5\,\text{m} (1\,\text{lift} = 5\,\text{m height})$$
$$= 15\,\text{m}$$

$$\text{Total Volume} = \text{Area} \times \text{Height}$$
$$3{,}558{,}750\,\text{m}^3 = \text{Area} \times 15\,\text{m}$$
$$\text{Area} = 237{,}250\,\text{m}^2 \left(1\,\text{ha} = 10{,}000\,\text{m}^2\right)$$
$$= 23.725\,\text{ha}$$

Compute the amount of leachate:

Using Eq. (8.2),

For old site (less than 4 years):

$$\text{Flowrates}, Q = 8\,\text{m}^3/\text{day} \quad \text{ha} \quad \text{lift}$$

$$Q = 8 \times 23.725 \times 3$$
$$= 569.4\,\text{m}^3/\text{day}$$

8.5 Classifications of Landfill Leachate Treatment

The treatment of landfill leachate can be done in a variety of ways. Researchers divided the various treatment methods into three categories: (1) traditional leachate treatment (leachate channelling-combined treatment with domestic sewage and recirculation), (2) biological treatment (aerobic and anaerobic methods), and (3) physico-chemical treatment (adsorption, chemical oxidation, coagulation/flocculation, chemical precipitation, air stripping, and sedimentation/flotation [22, 23]) (Fig. 8.8).

8.5.1 Leachate Channelling

The simplest way of leachate treatment, especially for newly constructed landfill leachate, is leachate channelling [24]. This is basically a combined treatment process with domestic sewage and recirculation of leachate through which leachate passes to the combined sewer system or is recycled back. Leachate channelling is preferable in certain cases because of its cost-effectiveness with simplicity in operation and maintenance [8]. Practically, this process is applicable where the landfills are closer to the wastewater collection system.

8.5.2 Recirculation

Recycling or recirculation of leachate is defined as returning the created leachate to the waste body. The presence of contaminants in the leachate is improved by the secondary infiltration of leachate through the waste body, which enhances further degradation. Because it is one of the most cost-effective methods, leachate recirculation is commonly used [25]. In recirculated leachate, there is a considerable reduction in COD and CH_4 formation. Furthermore, by increasing the moisture level in the waste, leachate recycling improves enzyme and nutrient dispersion. According to the findings by Abbas et al. [25], recirculation can increase COD elimination by up to 70%. Recycling not only improves the quality of the leachate but also greatly reduces the time it takes for the leachate to stabilize. Too much recirculation rate, on the other hand, may have negative effects on anaerobic degradation, causing significant organic acid concentrations, ponding, and saturation surrounding landfills.

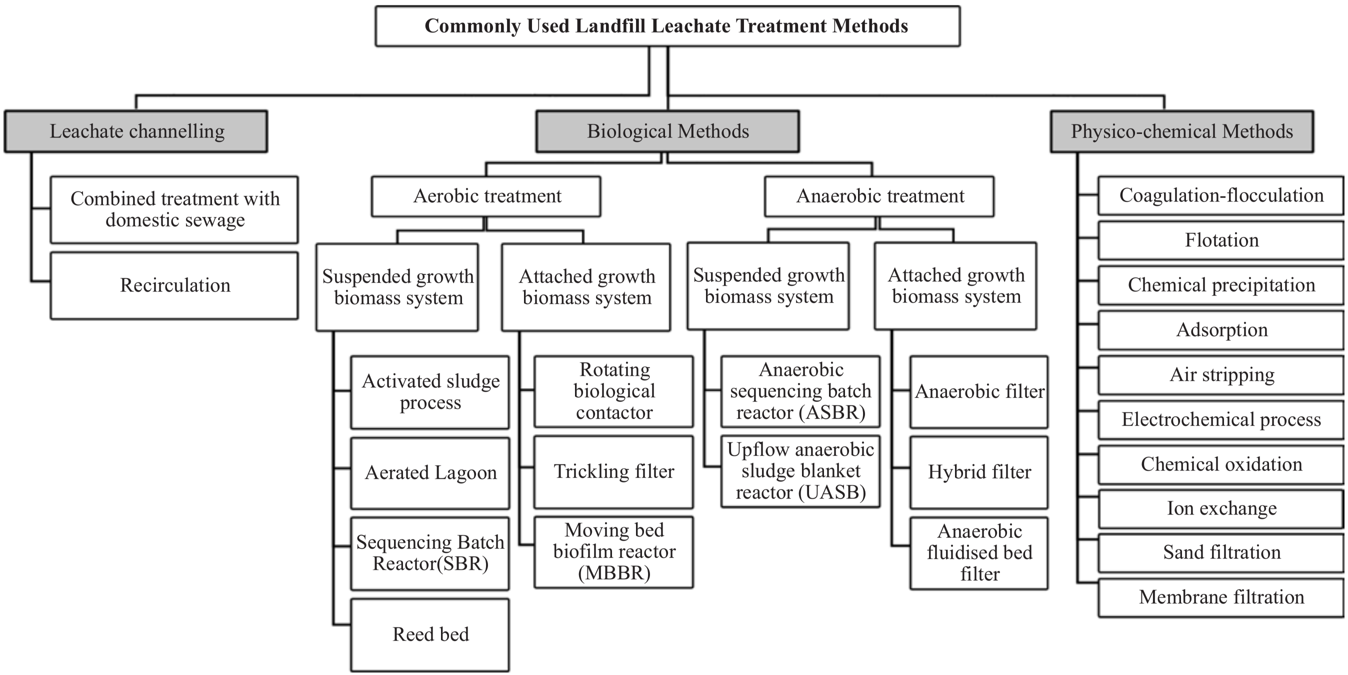


Fig. 8.8 Landfill leachate treatment methods

As a result, leachate recirculation could be used as a landfill management method as well as a leachate treatment. Leachate recirculation is accomplished by collecting leachate at the landfill's base and dispersing it throughout the waste body, usually via the gas venting system. Recirculation has been shown to reduce leachate chemical concentrations dramatically, even out the flow of leachate that must be discharged from the landfill for further treatment, and possibly improve landfill stabilization.

When compared to other landfill types, experiments with a lysimeter have shown that this approach speeds up leachate quality purification at semi-aerobic landfills. The recirculatory semi-aerobic landfill maximizes the solid waste layer's purifying capacity and accelerates the landfill's stability by returning collected leachate to the landfill site. The main goal of this treatment is to speed up the decomposition of the waste body, releasing gas and reducing the amount of time required for long-term monitoring and maintenance.

Using a low-cost recirculatory system, this procedure was used for the first time in an ASEAN country, Malaysia (using bamboo as leachate pipelines). The semi-aerobic state was maintained by recirculating leachate from a retention pond back to the gas venting pipes. Recirculating the leachate also promotes nitrification and denitrification, lowering the leachate's pollutant load and speeding up the waste stabilization process in the landfill.

8.5.3 Combined Treatment with Domestic Sewage

Leachate from nearby landfills flows into the sewerage system via a pipe network, where it is treated with domestic sewage at a traditional wastewater treatment plant [25]. Although combined treatment of leachate and sewage through channelling is a low-cost and operationally simple method, the existence of refractory organics with heavy metals in leachate and its lower biodegradability is a severe dilemma that may reduce the treatment efficiency.

The variations in physicochemical properties of leachate and sewage, as well as the volumetric ratio of loading, are the great challenges to fixing up the treatment mode. Therefore, researchers focused on optimizing the volumetric ratio for better treatment implementing several methods like sequencing batch reactor (SBR), adsorption with powdered activated carbon (PAC), etc.

8.5.4 Treatment

Leachate treatment mainly involves physical, biological, physicochemical and chemical treatment. As the leachate compositions vary significantly from site to site, an integrated system consisting of all of the above is normally necessary. These will be discussed in subsequent sections.

8.6 Landfill Leachate Treatment Methods

There have been numerous attempts to use physicochemical treatment technologies to treat landfill leachates. The efficacy of the biological process declines as the biodegradable organic content of the leachate decreases over time as a landfill stabilizes, and physicochemical processes may become one of the viable options. Physicochemical approaches have been suggested for the treatment of old and dilute leachate with low biodegradability. Physicochemical treatment is often more cost-effective than biological treatment and can be used for treatments in less time. In the physicochemical treatment, the physical characteristics of the medium are used to eliminate (chemically convert), separate, or contain the contamination. Physicochemical treatment methods include coagulation-flocculation, chemical precipitation, chemical oxidation, air stripping, adsorption, and membrane processes. All of the other procedures in this chapter are separation techniques, whereas oxidation techniques are destruction techniques. Separation residuals will need to be treated or disposed of, adding to the overall project costs and possibly requiring permits.

On the other hand, the efficacy of physicochemical treatment on leachate is highly dependent on its quantity, composition, and age. Before deciding on treatment options, the amount of leachate must be considered. As we all know, one of the most significant issues involved with the design, management, and long-term maintenance of landfills is managing leachate, which is created when water infiltrates through the deposited trash. Leachate generation rates are determined by the amount of liquid in the garbage at the time of disposal and the amount of precipitation that enters the landfill through infiltration or falls directly on the waste. The rate of leachate generation is critical to know, especially during the leachate treatment process.

The biological processes can be classified as aerobic (aerated lagoons, activated sludge, rotating biological contactors, trickling filter) or anaerobic (aerated lagoons, activated sludge, rotating biological contactors, trickling filter) (anaerobic filter, anaerobic sludge bed reactor). Biological procedures are often favoured for the treatment of leachate containing organic contaminants that has a high biodegradable value (BOD_5/COD ratio) and is mostly found in new landfill sites.

In contrast, data from over 150 landfills in Germany and Spain revealed that inorganic components make up 80–95% of landfill leachate, with just 5–20% organic matter [26]. As a result, biological degradation can only remove a limited number of contaminants from leachate, leaving a wide variety of contaminants such as heavy metals, bio-refractory materials, and halogenated organics. Other biological treatment limits for landfill leachate include:

- High levels of ammoniacal nitrogen, which has been shown to prevent microorganisms from degrading biologically [27].
- The biological treatment performed well in treating young landfill leachate, but it was unable to treat older leachate, which is primarily made up of refractory materials and contains numerous chemicals that hinder biological activity [27, 28].

- Low concentrations of substrate, such as phosphorus, that are required for microbe activities necessitated substrate addition [28].

Tables 8.5 and 8.6 show the components that can be eliminated by various biological and physicochemical processes.

Table 8.5 Summary of treatment process performance for various leachate types [23, 25, 29]

Treatment process	Target removal	Performance Type of leachate Young	Medium	Old
Combined treatment with domestic sewage	Suspended solids	Good	Fair	Poor
Recirculation	Improve leachate quality	Good	Fair	Poor
Activated sludge process	Organics	Good	Fair	Poor
Sequencing batch reactor (SBR)	Organics	Good	Fair	Poor
Aerated lagoon	Organics	Good	Fair	Poor
Reed bed	Organics	Fair	Fair	Good
Trickling filter	Organics	Good	Fair	Fair
Rotating biological contactor	Organics	Good	Fair	Poor
Moving bed biofilm reactor (MBBR)	Organics	Good	Fair	Poor
Anaerobic sequencing batch reactor (ASBR)	Organics	Good	Fair	Fair
Upflow anaerobic sludge blanket reactor (UASB)	Organics	Good	Fair	Fair
Anaerobic filter	Organics	Good	Fair	Fair
Hybrid filter	Organics	Good	Fair	Fair
Anaerobic fluidized bed filter	Organics	Good	Fair	Fair
Anaerobic lagoon	Organics	Good	Fair	Poor
Coagulation-flocculation	Heavy metals and suspended solids	Poor	Fair	Fair
Flotation	Suspended matter	Poor	Fair	Fair
Ammonia/air stripping	Ammonia or volatile organics	Poor	Fair	Fair
Chemical precipitation	Heavy metals, NH_3-N and some anions	Poor	Fair	Poor
Adsorption	Organic compounds	Poor	Fair	Good
Chemical oxidation	Organics; detoxification of some inorganic species	Poor	Fair	Fair
Electro-chemical process	Suspended solids and some inorganics	Poor	Fair	Fair
Micro-filtration	Suspended solids	Poor	Poor	Poor
Ultrafiltration	Bacteria and high molecular weight organics	Poor	Fair	Fair
Nano-filtration	Sulphate salts and hardness ions, like Ca (II) and Mg(II)	Good	Good	Good
Reverse osmosis	Dilute solutions of organic and inorganic compounds	Good	Good	Good
Sand filtration	Suspended matter	Poor	Poor	Poor
Ion exchange	Dissolved inorganics, anions/cations	Poor	Fair	Fair

Table 8.6 Different applications' performance in removing leachate parameters [30]

Treatment method	Leachate parameters					
	BOD	COD	SS	NH_3-N	Colour	Heavy metals
Activated sludge process	▲	●	Ø	Ø	Ø	Ø
Contact aeration process	▲	●	Ø	Ø	Ø	Ø
Rotary biodisk conductor process	▲	●	Ø	Ø	Ø	Ø
Biological trickling process	▲	●	▲	Ø	Ø	Ø
Biological nitrogen	▲	●	Ø	▲	Ø	Ø
Flocculation-sedimentation	●	▲	▲	Ø	▲	●
Sand filtration	Ø	Ø	▲	×	●	×
Activated carbon (adsorption)	▲	▲	●	Ø	▲	●
Chemical oxidation	×	●	×	×	▲	×

High (▲), Medium (●), Low (Ø)

8.6.1 Biological Treatment Methods

8.6.1.1 Introduction

The treatment uses biotic materials like organics or microorganisms as a catalyst, which is recognized as biological treatment. Biological treatments are very much effective for early stage leachate with a BOD_5/COD ratio ≥ 0.4 [31], which are applied normally to remove concentrated BOD and nitrogenous compounds from landfill leachate. Biodegradation of microorganisms to decompose the organic portion of leachate is the basic principle of this method. Biological treatments embrace mainly aerobic and anaerobic processes. After degradation of organics, sludge and CO_2, methane (CH_4) is formed for aerobic as well as anaerobic processes, respectively.

The effectiveness of biological treatment decreases in the course of solid waste biodegradation and because of increasing refractory humic acid or fulvic acid in leachate. These organics are not compliant with ongoing biological methods, and the existence of high ammonia is also an inhibitory factor for biological processes. However, previous researches firmly explained that biological methods are effective to treat comparatively young leachate (<5 years) while becoming ineffective for matured leachate treatment [23].

However, before the application of the biological treatment for landfill leachate, there are some uncertainties that must be reviewed in-depth. Previous researchers identified and claimed the qualitative variance and instability of landfill leachate [32]. However, to meet compliance requirements applying the biological procedures as sole treatment options is very tough while it shows far better performance than the pre- or post-processing methods. According to Peng [32], a trend towards overcoming the aforementioned shortcomings would be to combine biological treatment with any other appropriate treatment technology.

8.6.1.2 Factors Influencing Biological Treatment

Biological methods are preferred for landfill leachate treatment because of their environment-friendly nature and cost-effectiveness. Several factors influence the effectiveness of biological treatment, such as microbiological components, nutrients, pretreatment processes, inhibition factors, and environmental conditions.

8.6.1.2.1 Microbiological Components

Among the microbial components' bacteria are the amplest microorganisms that are widely utilized for the biological treatment of leachate. Bacteria are categorized based on their biochemical reaction, morphological structure, and DNA arrangements. Bacterial characteristics, biochemical reactions, and DNA sequence analysis are the widespread methods for detailing the bacterial category. Analysis of chemical reactions with appropriate chemicals and optimum conditions may lead to rapid and more precise output. Rounded cylindrical 'Bacillus' and spherical 'Coccus' are the well-known morphologies of bacteria having some other unusual morphologies (twisted or curved cylinder typed) [33].

8.6.1.2.2 Nutrients

Nutrients are the important things, which provides the sources of energy to the microorganisms. Bacterial growth is dependent on the availability of the nutrients contained in a certain environment, and the requirement of nutrients differs upon the types of microorganisms. Nutrients are helpful for the cellular biogenesis of bacteria and available in the form of macromolecules and micro molecules, inorganic and organic compounds, water, etc. Again, microorganisms can be characterized based on nutrient's intake.

8.6.1.2.3 Pretreatment Processes

Landfills receive diverse quality and quantities. Landfill leachate is a complex wastewater stream, which is the consequence of the solid waste decomposition inside landfills. This landfill leachate very often contains heavy metals and organic and inorganic compounds, which are hardly biodegradable by microorganisms. However, biological treatments of landfill leachate are influenced by several pretreatment processes as well because of the variety in content [34].

8.6.1.2.4 Environmental Conditions

The bacterial action for the biological treatment of leachate is closely related to environmental conditions and their metabolism. During biological treatments, bacteria consume lipids, carbohydrates, and protein, and it depends on environmental conditions as well as types of bacteria. For the growth and survival, each type of bacteria requires a separate environmental situation since hot weather is favourable for some bacteria, while some other types react maximum in cold weather [35].

8.6.1.2.5 Inhibition

Inhibition is an important factor before applying biological treatment since this is one of the major issues for the failure of treatment. Unfavourable environmental or treatment condition such as pH, aeration level, selection of appropriate bacterial culture is responsible for the bacterial inhibition generally. Determination of the by-products in every certain case is the indicator is the inhibition. The lesser production than average rate indicates the happening of inhibition, which is eventually the sign of reducing the efficiency of the treatment process [36].

8.6.1.3 Some of the Aerobic Biological Treatment

The presence of air is recognized as the term 'Aerobic', which involves the implementation of oxygen. Therefore, the methods performed in the presence of oxygen utilizing microorganisms (aerobes) are known as Aerobic Biological treatment. These methods apply free oxygen for the assimilation of organic contaminants through aerobes, which transform the impurities into CO_2, biomass, and water [37].

8.6.1.3.1 Activated Sludge Method

The activated sludge process is the application of microorganisms through a continuous supply of generated sludge (activated sludge) in a reactor with oxygen and organics (as shown in Fig. 8.9). After consuming the organics from leachate, the microorganisms go through the metabolic process for generating water and CO_2 containing new cells through this method [22]. Protozoa, fungi, yeast, bacteria, and other interacting organics are commonly available in activated sludge. The aerobic environment through aeration or diffusion needs to maintain continuity in the reactor.

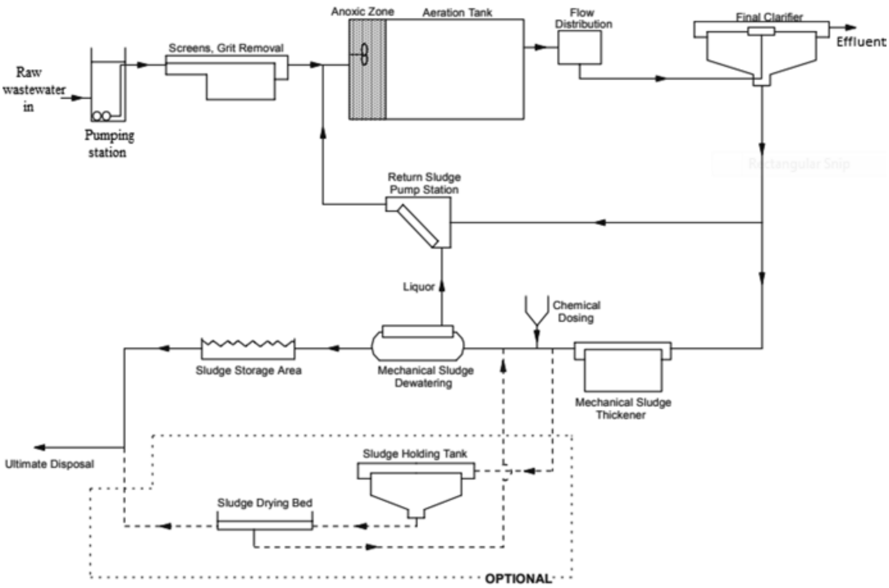


Fig. 8.9 A typical activated sludge diagram [38]

8.6.1.3.2 Membrane Bioreactor

A membrane bioreactor or membrane biological reactor (MBR) is the combination of conventional biological treatment (activated sludge) with a membrane separation technique like microfiltration or ultrafiltration for wastewater or leachate treatment. This system is now developed remarkably and is widely used for municipal wastewater and leachate treatment. Based on the membrane positioning concerning the organics in inundated (S-MBR) and outer (R-MBR) membranes, the membrane bioreactors are divided into several types [39].

Firstly, inside the oxidation tank, the membranes are submerged into leachate. A little bit of pressure difference is developed through a pump inside the filtration media for passing the treated effluent by membranes to obtain effective solid separation without sedimentation. Secondly, the effluent that comes from the oxidation tank is passed to the membrane filtration media, which is placed at the external portion of the aeration tank, and at the same time, the sludge is recycled towards the bioreactor. The removal efficiencies of COD, BOD for early stage leachate, or matured are related to membrane types. For a hollow-fibre or flat sheet bioreactor, the removal efficiencies of COD and BOD remain 67%–71% and 92%–93%, respectively. Besides that, flat sheet membranes perform substantially greater removal of ammonia (64%) and total nitrogen (62%) than hollow-fibre membranes (48% and 50%) [40]. Variation of temperature has a vital impact on removal efficiency as well, and 30–40 °C range is usually applicable for leachate treatment. The COD removal can enhance up to 80% with gradual increasing of BOD removal (up to 99%) [4]. Therefore, the outcomes regarding the removal for MBR demonstrate that a little bit higher temperature is suitable to boost up the COD and BOD removal exclusively from stabilized leachate with concentrated, dissolved organic matters. But, the MBR technology is not properly suitable for nitrogen removal, and an appropriate post- or pretreatment option can be considered [41].

MBR efficiently concentrates the biomass, reduces the requirement of tank size, enhances the bio-treatment method efficiency, and generates significantly disinfected as well as clarified effluent [42]. But, membrane fouling is the big issue, which causes the deterioration of the process efficiency because of several fouling substances [43]. The removal efficiency through MBR also fluctuates based on pH value. Thus, as MBR produces high-quality effluent, less sludge than the suspended biomass method, so it can be recognized as an efficient technology for young and matured leachate treatment with a high concentration of refractory dissolved organics [44]. Figure 8.10 shows a typical MBR mechanism and its system compared to a conventional activated sludge system.

8.6.1.3.3 Aerated Lagoon

An artificially constructed pond with microbes is typically termed an aerated lagoon, which has a wide similarity with an activated sludge reactor. Dissolved oxygen (DO) exists throughout in depth of it. However, it can also remain normally [8]. Microorganisms can grow easily in aerated lagoons during the long retention time. The long retention times of leachate in the lagoon promotes the oxidization of ammonia nitrification. Aerated lagoon allows flexibility of treatment method and can cope up with leachate of variable strength as well as flow, which are the advantageous concern of this method. Meanwhile, the requirement of a large area, greater heat loss, formation of odour, and lower efficiency of energy are the disadvantageous issues of this method.

Aerated lagoons or stabilized ponds is the easiest way of landfill leachate treatment especially onsite. This process is mostly applied in developing countries, which occurs through biological oxidation. However, hydraulic retention times (HRT) must be thoroughly evaluated before the aerated lagoon method can be used as a full-scale leachate treatment. For the most practical applications of full-scale treatment, HRT is calculated through the leachate inflow rates towards the reactors, which are typically dug ponds in the earth [46]. Higher COD removal efficiencies can be achieved through this process for early stage leachate with higher concentrations of COD. Even though 63% of ammonium removal can be accounted for by nitrification, but a major portion (37%) of the ammonium could not be removed through this process [46].

According to the various research outcomes, this process might achieve standard removal at long retention [4]. Therefore, an aerated lagoon system is proposed for the countries with widespread free spaces (as shown in Fig. 8.11), with almost no availability of energy and financial support.

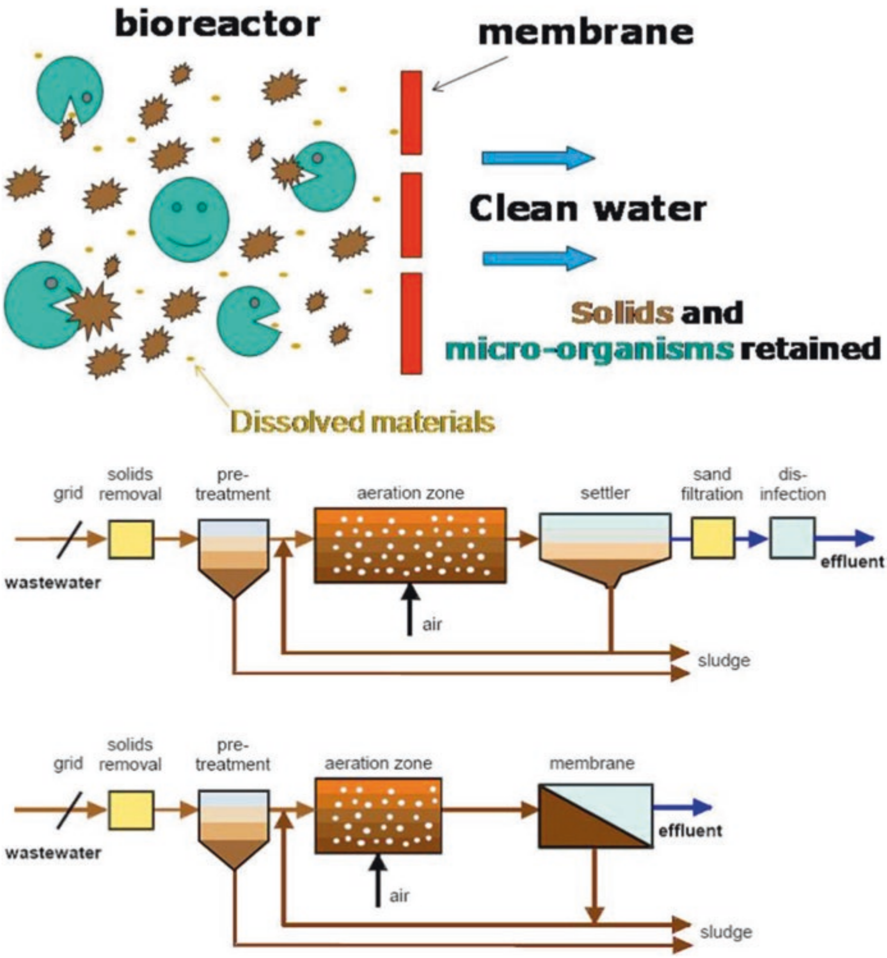


Fig. 8.10 A typical MBR mechanism and its system compared to a conventional activated sludge system [45]

8.6.1.3.4 Sequencing Batch Reactor (SBR)

The sequencing batch reactor (SBR) is a draw-and-fill treatment system for wastewater or leachate like activated sludge method, where the sludge settlement and aeration occur in the same tank following a batch mode through cyclic operations. Landfill leachate is added as a single batch reactor through this system for removing the pollutant components and discharged later. SBR is designed to operate under a continuous flow process and non-steady-state circumstances. The SBR process merges all treatment options and procedures into an individual tank or basin, whereas the conventional methods trust several tanks. Typically, SBR is segregated into five separate steps: filling, aeration and reaction, settle, draw, and idle [47]. The

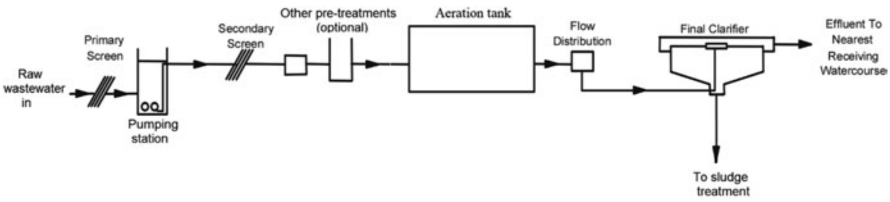


Fig. 8.11 A typical aerated lagoon

influent intake of leachate in the SBR basin or tank where microorganisms come into contact with organics is known as loading or filling. After leachate loading, oxygen injection or aeration occurs for facilitating the consumption of substrate through microorganisms that are recognized as biodegradation. Because of the carbon sources consumption at the aeration phase, leachate does not have enough sources of carbon in the subsequent anoxic denitrification phase, which eventually leads to a lower removal efficiency of total nitrogen (TN) [48]. Besides, due to the increment of influent ammonium, a reduction in organic compounds degradation happens in this method, which suggests necessary pretreatment. Hence, to ensure the effective implementation of landfill leachate carbon sources with low C/N ratios (<4) and accomplish the higher nitrogen removal without applying additional carbon sources, necessary modifications in SBR cycles are required [48]. Solid–liquid separation happens after the aeration stage, and eventually, treated effluent remains as supernatant above the settled sludge blanket (Fig. 8.12). Finally, decanting withdraws the treated supernatant from the reactor without unsettling the precipitates or sludge [47]. Based on the outcomes of Aluko et al. [49], SBR achieves the removal rates of different parameters from landfill leachate as chloride 27%, PO_3^{4-}-P 25%, ammonia 65%, suspended solids 63.28%, COD 75%, BOD_5 85.06%, along with the heavy metals removal zinc, iron, and cadmium (>65%).

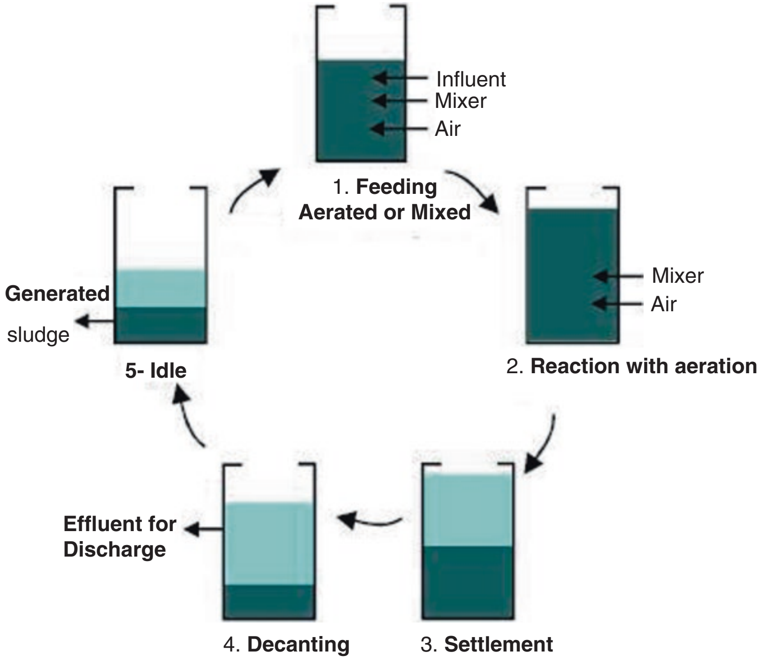
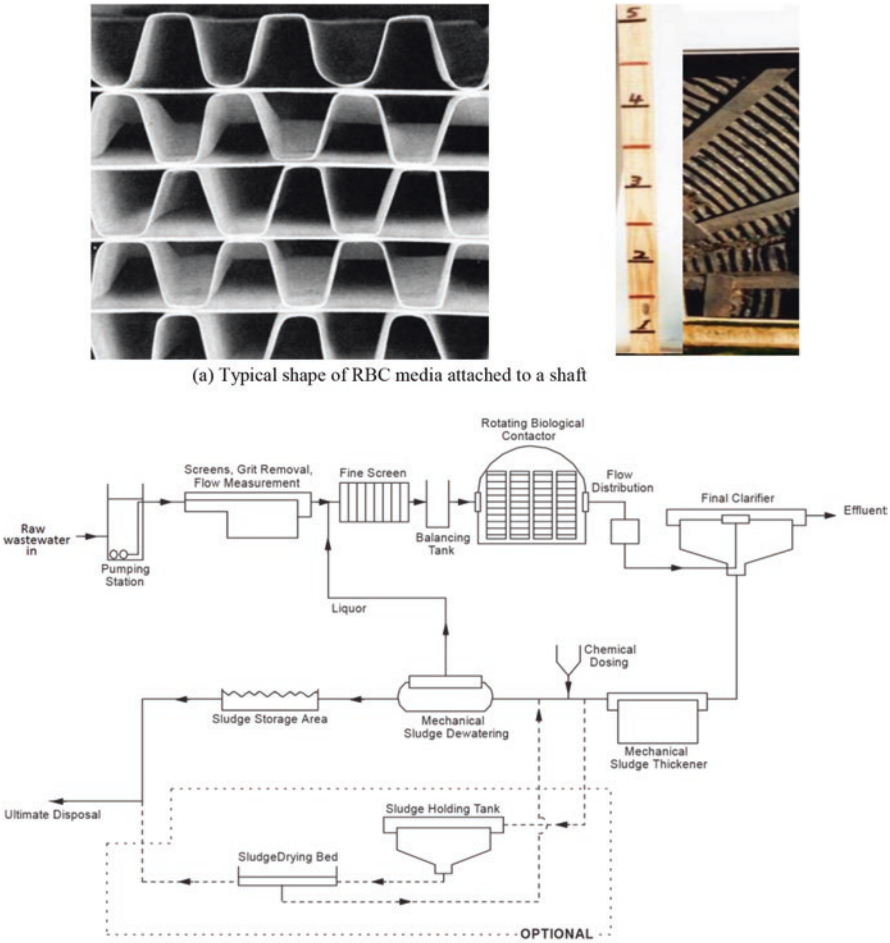


Fig. 8.12 Schematic diagram of sequencing batch reactor

8.6.1.3.5 Rotating Biological Contactor (RBC)

Rotating biological contactor (RBC) purifies leachate or wastewater of comparatively lower concentration through a series of attached plastic discs (polyvinyl chloride) with microorganism membranes. RBC is considered as a parallel method of traditional activated sludge technology. The rotating disks move slowly in a circular axis using horizontal shafts and maintaining around 40% submerged area in the leachate [50]. The plastic discs normally rotate about 5–10 rpm, and microbial pollutants from leachate cling to discs within 4 weeks, which eventually forms 2 mm thick biofilm. After getting thicker, the biofilm deploys from the discs [51]. RBC, in fact, is a *biological* method with fixed-film applicable mainly for lower concentrate leachate following primary treatment (Fig. 8.13). Coarse suspended or floating materials, sand, papers, and grit removal are the options that remain under the primary treatment *process* by screening, followed by the settlement of suspended solids.

The effectiveness of RBC for leachate treatment is correlated with a number of factors, such as hydraulic and organic loading, media applied, biofilm and leachate characteristics, rotating speed, DO level, solid and effluent recirculation, step feeding. According to earlier studies, RBC achieves a maximum of 95% ammonia, 40% COD, 80% BOD_5 removal from stabilized leachate [52]. Since a significant refractory COD still remains in RBC-treated leachate, so RBC is suitable with other biological or physicochemical treatment methods rather than as a sole treatment option [53].



(b) Process flow

Fig. 8.13 A typical process flow diagram of RBC treatment system [38]. (**a**) Typical shape of RBC media attached to a shaft. (**b**) Process flow

8.6.1.3.6 Trickling Filter

The trickling filter is an aerobic process, which is easy to construct and is widely used for sewage (industrial and domestic) and leachate treatment. Trickling filters consist of a fixed bed prepared with a granular substance through which leachate flows during treatment (Fig. 8.14). Thin biological film forms on this granular media, which exposes the air to uptake oxygen. External airflow creates an aerobic environment around the filter bed through natural convection. Rubber from tire chip, plastic, or wooden particles can be used as filling materials, which in fact take part in pollutant removal as well. However, the trickling filter method is recognized as less effective for wastewater with high organic concentration. Research studies

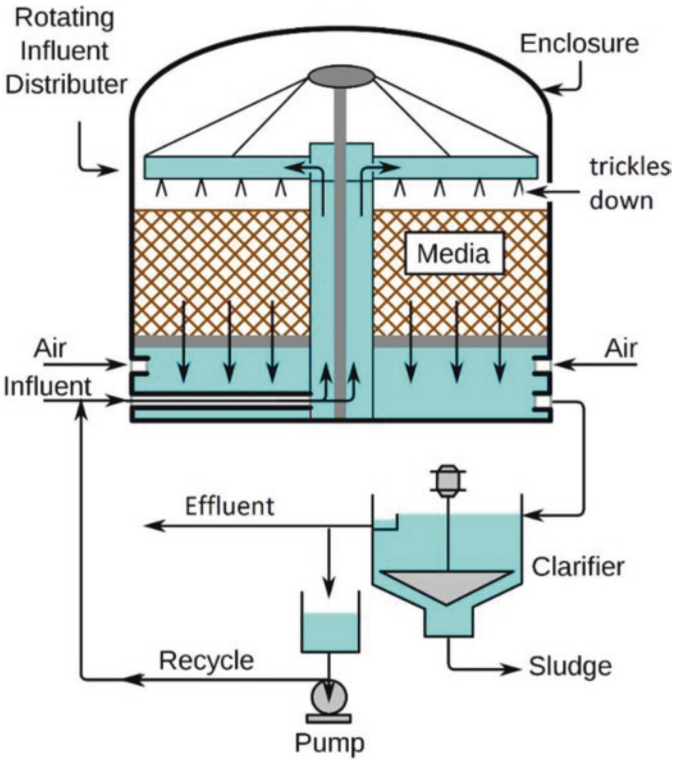


Fig. 8.14 Schematic diagram of trickling filter

reported 60% ammonia, 77% BOD_5, 72% turbidity, 74% suspended solids, and 49% COD removal by using the trickling filter method for landfill leachate [4]. Therefore, although in some specific cases, ammonia removal reaches up to 90% by this process, but NO_3-N concentration increases because of nitrification [49].

8.6.1.3.7 Moving Bed Biofilm Reactor

Moving bed biofilm reactor (MBBR), which is also known as fluidized bed reactor (FBR), is an extremely efficient biological method for leachate treatment, which was developed according to the traditional activated sludge process and is a biofilter consisting of the high specific surface area. MBBR is well-known for treating wastewater from the paper and pulp industry, poultry processing industry, refinery and slaughterhouse waste, and phenolic effluent [54]. The application of continuously moving suspended and porous polymeric carriers in the aeration tank is the basic concept of MBBR. In MBBR, the biofilm develops on rotating materials within the tank (Fig. 8.15). Depending on the application, the medium of the conveyor may have diverse sizes and shapes. Depending on the biomass required, they

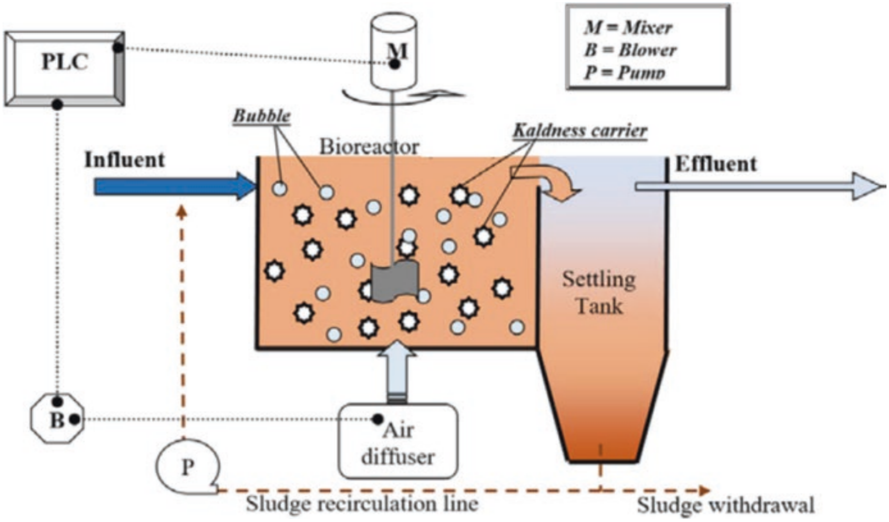


Fig. 8.15 Schematic diagram of a typical moving bed biofilm reactor [55]

may engage around 30–60% volumes in the reactor. MBBR is exclusively effective for COD, phosphorus, and nitrogen removal since the reactor includes nitrification, denitrification, and oxidation processes generally. A study reported, usually, MBBR can achieve 90% nitrogen and 20% COD removal only, but it can ensure around 60% COD and 90% ammonia removal from landfill leachate by improving the operating conditions [4]. Moreover, it is possible to reach the COD and ammonia removal up to 95% through introducing the aerobic phase after the anaerobic stages [54]. Granular-activated carbon can be applied as a porous material for organic matter adsorption, which eventually can optimize biodegradation. MBBR can remove an average 75% of refractory organic compounds through a coupling of adsorption with biological treatment methods. Around 70% tank volume reduction is an advantageous issue of MBBR. Higher biomass concentrations, very much minor sensitivity toxic compounds, and lower sludge settling periods are some other significant advantageous issues of this method. However, MBBR requires a large amount of energy for optimum ventilation with medium to large bubbles.

8.6.1.4 Anaerobic Biological Treatment Methods

Anaerobic treatment processes of leachate are dissimilar from aerobic systems, where oxygen is not required. This process includes two stages: the first stage is known as the acid phase, where organic acids are formed from the conversion of the complex organic compound by facultative microorganisms. Volatile organic acids are changed to CO_2 and CH_4 due to the anaerobic microorganisms in the second phase of this process. The methane produced from this process can be acquired and reused as an alternative energy source for heating the reactors [56]. Inorganic compounds such as sulphate, carbon dioxide, and nitrate are the electron acceptors in this process. Anaerobic treatments are effective regarding lower energy requirement, minimum sludge generation, and recovery of methane, but further treatment is required yet because of the high BOD and COD of the effluent. For the treatment of a very high volume of leachate or leachate from the very long-time operating landfills, anaerobic processes are generally applied. Anaerobic sequencing batch reactor (ASBR), up-flow anaerobic sludge blanket (UASB), and anaerobic filter (AF) are commonly applicable anaerobic bioreactors [33].

Four sequential phases are followed in the anaerobic digestion process, such as (a) hydrolysis phase where polymers are converted or hydrolysed to monomers (amino acids), which are water-soluble; (b) acidogenesis phase where organic monomers are reformed to fatty acids (short-chain), alcohols, hydrogen, and CO_2; (c) acetogenesis phase, where organic acids with high molecular weight generate H_2, acetic acid, and CO_2; (d) methanogenesis phase where methane (CH_4) and CO_2 are produced from acetic acid finally [57]. At every stage, different environmental conditions and various growth rates involving bacteria are observed [58].

8.6.1.4.1 Anaerobic Sequencing Batch Reactor (ASBR)

The anaerobic sequencing batch reactor (ASBR) is a biochemical leachate treatment method, which functions in the absence of oxygen. Generally, anaerobic bioreactors are a combination of processes, including the biological disintegration of organic matter under anaerobic conditions (Fig. 8.16). The ASBR process follows the batch treatment method naturally with 7 days' cyclic duration; the refilling stage continues for 5 days with an ongoing reaction stage.

However, the reactor settlement and release phase are happened in these two additional days and on day 7. About 22–39% of total reactor volume is the total interchange volume in this process [59]. Lipid degradation happens gradually than sludge, while sludge takes more time for complete degradation in a batch. There are four steps to follow in an anaerobic sequencing batch reactor (ASBR) such as feeding (20 min), reaction (2 h), settling (1.5 h), and decanting (20 min). Usually, ASBR is not an effective method for weak or less concentrated leachate because of lower gas generation and inadequate turbulence, which leads to the resistance for external mass transfer.

ASBR can remove the implementation of settling tanks since it can obtain the organic removal or solid capture in a singular tank. The previous studies reported that the COD removal efficiency is around 80%, and the daily yield of biomass conversion is around 0.1 g volatile suspended solids. But, in the case of the combination of anaerobic and aerobic reactions in SBR, maximum of 44% NH_3-N, 45% PO_4, and 75% COD removal were observed.

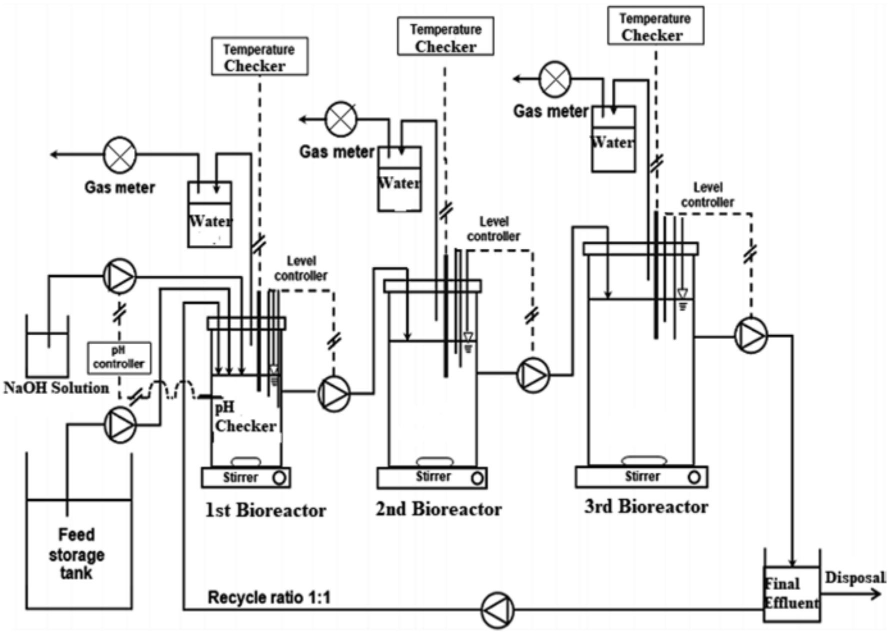


Fig. 8.16 Schematic diagram of anaerobic sequencing batch reactor (ASBR) [60]

8.6.1.4.2 Up-Flow Anaerobic Sludge Blanket (UASB)

The UASB reactor, or up-flow anaerobic sludge blanket method, is an anaerobic methane-producing digester used for leachate and wastewater treatment. The UASB reactor forms a granular sludge blanket by the anaerobic microorganisms (Fig. 8.17). The UASB reactor is one of the most efficient anaerobic digestion processes, which has drawn huge research attention in recent decades [61]. This is an up-to-date technique of leachate treatment with higher treatment efficiency and lower hydraulic retention time (HRT).

UASB includes an upward channel of leachate through an anaerobic sludge bed within a tank. As leachate moves through the sludge, microorganisms in the sludge absorb and decompose the organics. Biogas (methane and carbon dioxide) is generated because of the consequences of this process. Hydraulic turbulence in the reactor occurs when the gas rises to escape, causing mixing and allowing further interaction between substrate and microorganisms. Biodegradation is aided as a result of this phenomenon. The gas is stored at the reactor's apex. The sludge settles, and the effluent (supernatant) is discharged.

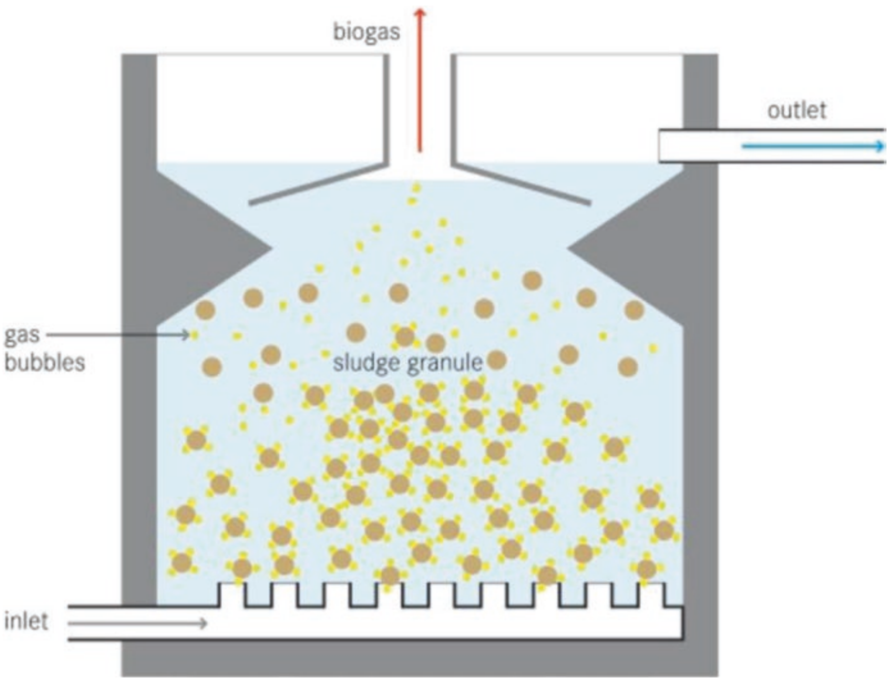


Fig. 8.17 Up-flow anaerobic sludge blanket schematic diagram [62]

8.6.1.4.3 Anaerobic Filter

The filter media containing abundant bacteria inhabitants, which decompose the organic compounds of landfill leachate is commonly recognized as anaerobic filters. This phenomenon passes slowly through the filter medium. In this process, the filter media behaves as a filter and, at the same time, as a biological contactor, which eventually eliminates the requirement for an isolated sedimentation phase. However, the generation of biogas (carbon dioxide and methane) happens commonly in this process.

8.6.2 Future Prospects of Biological Methods with Major Challenges

A range of biological leachate treatment technologies have continued to emerge in recent years, and despite having some problems, they have achieved good results. The common problems associated with biological treatments are high initial investment, higher operational cost, temperature effect, large area requirement, long detention period, and so on. In recent years, anaerobic treatment processes have developed especially for leachate with high organic content. The long retention period, relatively low contaminant removal, and sensitivity to the temperature change are the drawbacks of anaerobic processes. A combination of aerobic and anaerobic can show a better performance, but it also involves high operational and management costs as well as a potential threat for nearby water treatment facilities because of high leachate concentration in the outlet. Even it is quite difficult to handle and maintain the discharge standard with the anaerobic–aerobic combination.

However, it is ineffective for leachate treatment to apply solely biological methods. Rather, because of operational easiness environment-friendly behaviour followed by higher social acceptance, biological treatments are still preferable with great prospects in future as well. However, transforming these possibilities into reality has proven to be a difficult task. As a result achieving optimum treatment in terms of the efficiency of treated leachate for reuse or recycling continues to be a difficult challenge.

8.7 Physical Treatment Methods

Landfill leachate is a highly contaminated wastewater containing harmful heterogeneous compounds, the characteristics of which are directly related to the age of the landfill. The leachate from young landfills usually consists of a lot of biodegradable and eco-friendly ingredients, which can easily be treated by applying biological processes. On the other hand, leachate from stabilized landfills typically consists of refractory dissolved organics, which are non-biodegradable, and physicochemical methods are the better options to treat this type of leachate. Physical treatments utilize natural forces such as Van der Waal forces, electrical attraction, or gravity with some physically applied membranes. Physical treatment methods promote the agglomeration of dispersed elements, which may cause the change in the physical state but do not influence the chemical structures of the substances. The well-known physical methods of leachate treatment encompass aeration, floatation, sedimentation, adsorption, evaporation, or membrane filtration [63].

8.7.1 Air Stripping

The process of getting air into the leachate, also known as aeration, is known as air stripping. Air stripping is a technique for removing hydrogen sulphide (taste and odour), carbon dioxide (which reduces the need for lime), and volatile organic pollutants (VOC). The air stripping process depends on the efficiency of contacts between the phases (air and leachate) and optimizing the area of contact between the two. Two types of operations that can be used in the process are stripping basins (diffused and mechanical aerated) and stripping towers (spray, trayed, or packed tower). Many studies have documented the use of air stripping as an alternative leachate treatment for lowering ammoniacal nitrogen, in which ammonia was removed from the leachate by the volatilization of ammonia in the form of gaseous. The following is a formula for the transition of ammoniacal nitrogen:

$$NH_4^+ + OH^- \leftrightarrow NH_4OH \leftrightarrow H_2O + NH_3\left(g\right)$$

With a 1-day retention duration, Cheung et al. [64] were able to remove 65–74% of ammoniacal nitrogen from leachate in free stripping tanks. Air stripping can also reduce the toxicity of leachate, according to Silva et al. [65], because a high concentration of ammoniacal nitrogen in leachate has been linked to a high toxicity value. At high pH levels, ammonia nitrogen removal via air stripping is preferred, as shown in the reaction (presence of OH^- ions). To convert the majority of ammoniacal nitrogen to gaseous forms, high pH values between 10.5 and 11.5 are usually preferred. At pH 10 and 11, Ozturk et al. [66] only removed about 20% of ammoniacal nitrogen but achieved a high removal of 72% at pH 12. Lime or other chemicals must be added to improve the pH value of leachate, which is normally lower. Because ammonia is a very soluble gas, it requires a considerable amount of supplied air to effectively extract ammoniacal nitrogen from the leachate.

The air stripping process is also influenced by the ambient temperature, as low temperatures inhibit ammoniacal nitrogen removal. Marttinen et al. [67] found that at temperatures of 20 °C and 6 °C, ammonia elimination was 89% and 64%, respectively. In frigid temperatures, this is owing to an increase in ammonia gaseous solubility, which lowers air vapour pressure. In cold climates, heating of the leachate or the stripping system would be required to achieve better ammoniacal nitrogen removal in a shorter treatment period. Air stripping is only effective for removing a significant amount of ammonia nitrogen and about 25% of COD [66]. The production of a significant amount of ammonia gaseous, calcium carbonate scaling (caused by the use of lime or acoustic soda for pH correction), and ammonia stripping tower foaming are all disadvantages of the air stripping process.

The emission of ammonia into the environment is considered a serious air pollution concern that necessitates the use of an effective adsorbent system. H_2SO_4 or HCl is frequently used to treat this gas. When a high number of times are utilized for pH adjustment prior to the air stripping procedure, the calcium carbonate scaling problem occurs. When dealing with old leachate, which has high alkalinity and a strong pH buffering mechanism, this problem frequently arises. Scaling is caused by the use of a large amount of acid to absorb the released ammonia from the treatment. Foaming caused by leachate stripping can be avoided by employing a big stripping tower or regulating the airflow if a small tower is used (lengthen the retention time). These kinds of issues can lead to serious operational and maintenance issues. In terms of cost, air stripping to remove ammonia is the most effective and least expensive alternative treatment technique [66].

8.7.2 Flotation

Flotation is a well-known separation method widely used in wastewater or leachate treatment, which is in practical application since early 1920. Although the flotation method is commonly applied for mineral processing, there are significant differences between its application in mineral processing or wastewater treatment regarding bubble sizes and surface area, shear stress, and forth stability. Meanwhile, the flotation method can be categorized into dissolved air flotation (DAF) and dispersed air flotation [68]. Therefore, DAF is the favourable flotation method for leachate treatment while dispersed or forth flotation for mineral processing.

DAF creates bubbles by lowering the pressure of pre-saturated water with high-pressure air (greater than atmospheric pressure). Initially, DAF was implemented as a preliminary treatment method, whereas, in the course of time, researchers investigated the potential of DAF for the diversified application in wastewater and leachate treatment. Zhang et al. [69] determined the efficiency of pressurized aeration with DAF for the treatment of domestic wastewater. There are alternative flotation processes also applicable for wastewater treatment, such as induced air flotation (IAF) of electro-flotation (EF). Although the focus of the flotation method is mainly on wastewater treatment, studies have been going on recently to focus on the leachate treatment as well. Palaniandy et al. [70] investigated the use of DAF in semi-aerobic landfill leachate to remove colour, COD, and turbidity. Positively, Zouboulis et al. [71] used the flotation method to remove humic acid from biologically treated leachate, and Adlan et al. [72] demonstrated the efficacy of coagulation and DAF for semi-aerobic landfill leachate treatment.

8.7.2.1 Working Principles of Flotation

The flotation method is closely related to the air bubble producing technique and its application. Air bubbles attach to floc particles and reduce the density lower than the water, which eventually allows the flocs to float towards the water surface [73]. Although dispersed air, electrolytic, or dissolved air methods are applied for bubbles generation, DAF is the most applied for wastewater treatment with high potential for the application in leachate treatment as well. The DAF chamber is divided into contact areas as well as separation areas. The contact area promotes the attachment of bubbles and particles, allowing enough time to collide and attach [74]. The flocs form particle–bubble agglomerate within this contact area and create a flow towards the separation area with water and detached particles. Meanwhile, the separation area pushes the particle–bubble agglomerate to the top of the tank, and the remaining conglomerates flow with water and separate in the filtration phase. It is reported that the high efficiency of floatation reduces the backwashing frequency of filter media as well as increases the filter longevity [74]. Bubble properties such as size, shape, bubble concentrations in the zone of contact, and charge are the key factors, which determine the effectiveness of the bubble–particle collisions and attachment through floatation.

8.7.2.2 Bubbles Size, Shape, and Concentration

The bubble size is generally measured by Stoke's theorem by rising velocity [33]. The average bubble size observed in the contact zone is around 60–80 μm, and this size inversely varies with the saturator pressure. Bubble size also increases a bit when it floats slowly to the leachate surface. In the DAF system, the small size bubbles can captivate more particles, which eventually accelerate the removal of particulates from leachate or wastewater. But, small-sized bubbles require more rising time and larger cell for the treatment, which ultimately cause the inefficiency of the method for higher effluent loading [75]. Still, DAF is recognized as an efficient method, especially for small particles [76].

The pressure reduction of saturated water after the separation zone causes the bubble generation in DAF when the effluent flows through small orifices. These bubbles become spherical shaped when it goes up to the upper surface. So, the spherical shape concept is followed in the DAF model. According to Leppinen and Dalziel [77], the removing bubbles and particles remain spherical, whereas the density of the bubbles is higher than the density of the particles. The size and shapes of bubbles are related to several factors, i.e. injection device and its flow rate, bubble growth, and rising velocity [76]. However, for proper agglomeration to form a solid sphere with uniform speed and equivalent density, particles are required to attach with a number of bubbles of different sizes and shapes [33].

8.7.3 Sedimentation

Sedimentation is one of the physical treatment methods for wastewater or leachate treatment. This method utilizes the settling tendency of suspended particles within leachate due to gravity to remove the pollutants. The sedimentation method is effective as a part of the combined process for leachate treatment with the physicochemical or biological treatment rather than sole application. Primary and secondary clarifiers, which are settling tanks with a mechanical system for the deposited solid exclusion continuously, are provided to eliminate the dragged solids by the sedimentation process. Suspended solid particles of 10 μm or greater in size can settle due to gravity within a certain duration whereas, the colloidal particles (0.001 μm to 1 nm) are not likely to settle down due to the action of gravity because of gravity balancing by electrostatic force and Brownian motion.

The removal of suspended particles through the sedimentation process is related to several factors such as specific gravity, zeta potential, and particle size. Settled solids are measured from the visible volume deposited at the bottom of clarifiers after optimum duration. The relationship between the particle diameter and settlement rate can be explained by Stokes' law. Within certain conditions, the settling rate is directly proportional to the square value of particle diameter and inversely proportional to effluent viscosity. Specific design, as well as the operating system of clarifiers, is very much essential to continue the sedimentation process smoothly with a minimum threshold and to maintain the stream stability and transport system for entering sediments. The stream velocity needs to be lowered for the longest possible time to achieve this condition. Moreover, a wide approach channel and lower floor space promote better sedimentation of suspended particles through gravity.

8.7.4 Adsorption

Adsorption is identified as a separation method of solvable particles from liquid or gaseous phase through passing across the permeable media and forming a superficial monomolecular coating upon a substrate. This process can occur within the external side of the solid structure or in the proximity of the compact surface [78]. Adsorption is recognized as an efficient treatment method regarding various types of pollutant removal from leachate and wastewater. Adhesion onto permeable media surfaces is the basic removal mechanism through this process. The permeable media surfaces for adsorption is stated as 'adsorbent', whereas the adsorbed elements from liquids and gases are termed as 'adsorbate' [79]. For a long time, activated carbon, either granular (Granular Activated Carbon-GAC) or powdered (Powdered Activated Carbon-PAC), has been the most effective adsorbent for removing COD, heavy metals, and NH3-N from stabilized leachate. Following the vast effectiveness of this method regarding leachate treatment, numerous researches have been conducted for improving the application. Recently, low-cost carbonaceous natural substances such as sawdust, tea leaves, banana stem, or rice husk are getting more attention as alternative adsorbents because of their eco-friendly nature. Naturally available other materials like zeolite and limestone are also investigated as potential adsorbents.

8.7.4.1 Mechanism of Adsorption

The adsorption process makes use of materials or media that may adsorb dissolved molecules in water onto their porous surfaces. Adsorbents are the materials that adsorb substances, while adsorbates are the compounds that are adsorbed. Physical adsorption, chemisorption, and electrostatic adsorption are the three types of adsorption mechanisms. Chemisorption is fuelled by a chemical reaction that creates a chemical connection between the adsorbate and the adsorbent's surface, whereas physical adsorption is fuelled by weak molecular interactions like Van der Waals forces. The exchange of cations or anions between the pollutants and the exchange medium removes ions from the aqueous phase. Ion exchange is a type of electrostatic adsorption that involves the adsorption of ions via Coulombic forces. Many factors, such as adsorbate chemical properties, adsorbent properties, and leachate characteristics, could influence the leachate adsorption process. In landfill leachate, which contains a wide range of pollutants, certain compounds in wastewater adsorb and alter each other's adsorption capabilities.

For the optimization of the adsorbent application, a firm understanding of the interaction between adsorbent and adsorbate is very much essential. Adsorption is fundamentally a mass transfer method where substances travel from the liquid or gaseous phase to the solid adsorbent surface to form attachments through physical or chemical interactions [80]. The substances that travel to the solid adsorbent surface is defined as adsorbate. Moreover, the adsorption process depends on the dynamic and energetic sites of the adsorbent surface. Generally, two types of adsorption mechanisms are commonly applied; the process through physical forces is termed as physical adsorption or physisorption while applying chemical reaction for adsorption is known as chemisorption.

The relationship between the amount of adsorbates that accumulate on the adsorbent and the equilibrium concentration of dissolved adsorbate in the solution is described by an adsorption isotherm. Freundlich and Langmuir's equations are two mathematical equations that are often used to represent the adsorption relationship of an adsorbent. Because it is simpler, has no convergence, and produces particularly good regressions at intermediate concentration levels, Freundlich is a more often used equation [81]. Freundlich equation is written as in Eq. (8.4):

$$\frac{X}{M} = kC_e^{1/n} \tag{8.4}$$

where X mass of the adsorbate, M mass of the adsorbent, C_e equilibrium concentration of the remaining substrate in the water, k and n constants.

The adsorption capacity (X/M), which indicates the ratio between the adsorbate and the adsorbent, is an important measure for evaluating the adsorption impact for a certain adsorbent (mostly activated carbon). The effluent value determines the adsorption capability (C_e). The equation can be simplified as in Eq. (8.5):

$$\log\frac{X}{M} = \log k + \frac{1}{n}\log C_e \tag{8.5}$$

On log-log paper, an adsorption isotherm graph for X/M vs C can be made, yielding a straight line with slope $1/n$. The adsorption isotherm will express the amount of substrate adsorbed per unit mass of adsorbent based on the substrate concentration in the leachate. The adsorption isotherms are calculated using data from laboratory tests. Normally, adsorbents are utilized as a filtration system. The breakthrough time, t_b, can be computed using the following Eq. (8.6):

$$t_b = \frac{(x/m)_b\, Mc}{(Q)(C_i - C_b/2)} \tag{8.6}$$

where t_b time to breakthrough (day), $(x/m)_b$ field breakthrough adsorption capacity (g/g), M_c mass of adsorbent (limestone) (g), Q flow rate (m^3/day), C_i influent leachate concentration (mg/L), C_b breakthrough leachate concentration (mg/L).

8.7.4.1.1 Physical Adsorption

Physical adsorption or physisorption occurs because of the physical attraction of the Van der Waals forces of adsorbate to the adsorbent overwhelming the kinetic forces [78]. Physisorption is involved with nonspecific reactions because of its association with various physical forces and compounds. During this phenomenon, basically, the contact is escorted with weak interacting forces, i.e. intermolecular reactions like field dipole, polarization, which are the result of electronic or geometric properties of adsorbent and adsorbate [78]. Bonding energy and weak forces between adsorbent and adsorbate cause the reversibility of the adsorption process. Solubility of adsorbate in water or any other solvent is also an influential factor since higher adsorption observes at lower solubility of adsorbate in water and vice versa.

8.7.4.1.2 Chemical Adsorption

The adsorption process that involves electron transferring or sharing between adsorbent and adsorbate is termed chemical adsorption or chemisorption. In the case of chemisorption, strong chemical bonds (ionic or covalent) are formed, engaging intermolecular forces between adsorbent and adsorbate [82]. Practically chemisorption results in irreversible monolayer adsorption because of strong interaction between adsorbate and adsorbent surface where more than one layer cannot be accumulated. Short-range repulsive force, dispersion, H-bonds, or covalent bonds may happen through the chemical adsorption process. Moreover, the polarized nature of adsorbate may cause electrostatic forces involving dipolar interaction. Because of the energy released by these interactions, the adsorption process becomes exothermic.

8.7.4.2 Adsorption Isotherms and Kinetics

Adsorption isotherm and adsorption kinetic explain the synergistic behaviour amid concentration that accumulate in adsorbent and equilibrium concentration of adsorbate during adsorption process through the analysis of experimental data [83]. From the experimental process, the adsorption capacity at equilibrium is acquired using the mass balance in Eq. (8.7) [82]:

$$q_{\mathrm{e}} = \frac{V}{M}\left(C_0 - C_{\mathrm{e}}\right) \tag{8.7}$$

where q_e concentration solute adsorbate at equilibrium (mg/g), C_0 and C_e initial and equilibrium concentration of adsorbate (mg/L), V volume of sample (mL), M mass of adsorbent (g).

Meanwhile, adsorption isotherms are implemented for verifying the experimental data with an explanation of the interaction between adsorbent and adsorbate through the process, whereas the adsorption kinetics demonstrate the efficiency of the adsorption process through the adsorbate concentration concerning with time and adsorption rate is measured through a mass transfer process [79]. Several isotherm models are implemented to understand the in-depth facts from the experimental outcome. Among the commonly known isotherm models, Langmuir and Freundlich are very widely applied [84].

8.7.4.2.1 Langmuir Isotherm

The Langmuir isotherm model equation assumes that chemisorption interaction results in monolayer exposure of adsorbate over a consistent adsorbent surface, with sorption occurring at a specific homogenous site. Thus, the Langmuir isotherm model can explain various types of sorption processes, which can be written as follows (Eq. (8.8)):

$$\mathrm{q_e} = \frac{qbC_e}{1+bC_e} \tag{8.8}$$

where q_e amount of adsorbate at equilibrium concentration, q maximum adsorption capacity (mg/gm) to complete monolayer, b adsorption energy, C_e equilibrium concentration of sample.

Besides, the linear form of the Langmuir isotherm equation can be written as follows (Eq. (8.9)),

$$\frac{C_e}{q_e} = \frac{C_e}{q} + \frac{1}{bq} \tag{8.9}$$

8.7.4.2.2 Freundlich Isotherm

The Freundlich isotherm model equation assumes the adsorption process on a heterogeneous surface comprising different adsorption sites with numerous classes. The adsorption process assumes not limited to monolayer adsorption but embraces reversible multilayer adsorption also. Therefore, the model describes multilayer adsorption with surface heterogeneity and non-uniform energy level distribution. The Freundlich mathematical equation can be expressed as follows (Eq. (8.10)):

$$q_\mathrm{e} = K_\mathrm{f} C_\mathrm{e}^{1/\mathrm{n}} \tag{8.10}$$

And the linear form of Freundlich mathematical equation can be written as (Eq. (8.11)):

$$\log q_e = \log K_\mathrm{f} + 1/n \log C_e \tag{8.11}$$

where K_f Freundlich affinity coefficient (L/mg), n Freundlich exponential constant, which represents the adsorption capacity, q_e and C_e represent as earlier.

Adsorption kinetics describe the interaction between adsorbent and adsorbate regarding the adsorptive uptake as well as control the experimental efficiency. A little time for equilibrium reaction implies decent properties of adsorbent [85]. The most commonly available kinetic models for anticipating adsorption mechanisms are pseudo-first order and pseudo-second order.

The pseudo-first-order kinetic model can be written as (Eq. (8.12)):

$$\log\left(q_e - q_t\right) = \log\left(q_t\right) - \frac{K_1 t}{2.303} \tag{8.12}$$

The pseudo-second-order kinetic model can be written as (Eq. (8.13)):

$$\frac{t}{q_1} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \tag{8.13}$$

where q_t and q_e amount of the pollutant adsorbed (mg/g) at time t and equilibrium, K_1 (min^{-1}) equilibrium rate constants of pseudo-first order, K_2 (g/mg min) equilibrium rate constants of pseudo-second order.

Basically, pseudo-first-order kinetics demonstrates the physisorption technique of adsorption, while the second-order model assumes the chemisorption through ion exchange or sharing.

8.7.4.3 Adsorbents

8.7.4.3.1 Activated Carbon

Although several materials can be used as adsorbents, the most commonly used adsorbent for water treatment, including leachate, is granular or powdered activated carbon [86–90]. Typical commercial carbon has a total surface area of between 450 and 1500 m^2/g. Activated carbon is preferred for the adsorption process because of its ability to remove a wide range of adsorbates. There are few studies on the use of activated carbon for leachate adsorption, and the majority of those that have been done so in conjunction with other treatment processes like biological treatment, chemical oxidation, and membrane processes [88]. The use of PAC for adsorption can remove 38% of COD at a concentration of 2 g/L [88].

According to Morawe et al. [90], activated carbon columns can remove non-biodegradable materials as well as the colour that remains after biological treatment. According to the tests, carbon had a high efficiency for halogenated hydrocarbon (AOX) adsorption and preferred low molecular mass compounds over high molecular mass compounds, implying that high MW compounds had a smaller surface area for adsorption. Activated carbon has the ability to adsorb low MW organics in leachate, according to Imai et al. [86], Ehrig [91], and Pirbazari et al. [92]. Pirbazari et al. [92] discovered that leachate containing a high concentration of phenol, benzoic acid, and chlorobenzoic acid had significantly higher adsorption onto activated carbon removal effectiveness than leachate containing a low quantity of VOC. The adsorption of large molecular mass by activated carbon may clog pores, reducing the material's adsorption capacity.

COD and ammonia nitrogen can often be removed by carbon adsorption to the tune of 50–70% [91]. Ehrig [91] also claimed that the isotherm slope for acetic acid leachate, humid acid, and acetic acid leachate adsorption was too steep, making it unsuitable for such leachate treatment. Despite the fact that the effluent value was still high despite the slopes not being very steep, the same could be said about the methanogenic phase and biologically treated leachate. As a result, a combination treatment would be required to treat leachate until it reaches the discharge level.

8.7.4.3.2 Low-Cost Adsorbent

In order to use a low-cost adsorbent in the treatment of waste, wastewater, and leachate, a number of research projects have been undertaken. Among them are cocoa shells, zeolite, vermiculite, kaolin, activated alumina, bottom ash from municipal waste incinerators, charcoal, and limestone [93, 94]. These materials are much cheaper than activated carbon, and some of them are leftovers from local businesses. Table 8.7 lists the different types of low-cost adsorbents that were tested for wastewater treatment, as well as their origins. These materials have the potential to be used in leachate treatment.

Heavey [95] looked into the use of peat (raised bog) as an adsorbent in the treatment of leachate. His lab tests revealed that the material could be used to treat leachate at a low cost. According to laboratory column investigations, the procedure was capable of eliminating more than 80%, 60%, and 70% of CBOD, COD, and NH_4-N, respectively. Peat's cation exchange, on the other hand, restricts ammonia removal. According to Aspinwall [96], only 6% of peat's available cation exchange capacity (CEC) was used for ammonia removal. Ammonia is only temporarily stored in the peat column as an adsorption site before being liberated into other forms of nitrogen, such as nitrate. As a result of the nitrification process, the peat treatment procedure also demonstrates the potential to remove ammonia from leachate. The performance of peat for leachate treatment was shown to be promising in an onsite investigation.

Kaolinite has also been used to remove heavy metals from landfill leachate. According to the research, substances with a high molecular weight (MW > 1000 and > 12,000) were linked to the sorption of Pb, Cd, Ni, and Cu. This is because compounds generated by Fe and P have a high MW, whereas Zn has an MW of less than 1000 [97]. Because of precipitation, the isotherm from the batch study revealed concavity upward. Meanwhile, Majone et al. [98] observed a similar behaviour of lead adsorption onto kaolinite. An S-shaped isotherm was produced in the

Table 8.7 Type of low-cost adsorbent [99]

Types	Origin and structure
Limestone chip	As a by-product of the marble industry. Calcium carbonate is the primary component (>90%)
Zeolite	Hydrated aluminosilicates are made up of alumina and silica tetrahedral layered symmetrically. Chabazite, clinoptilolite, erionite, ferrierite, phillipsite, mordenite, and analcime are examples of natural zeolite
Clay	Also, hydrated aluminosilicates, but unlike zeolite, they have a distinct structure. Clay minerals are made up of layers of tetrahedral and octahedral structures. Illite, vermiculite, and smectite are three mineral groups found in clay
Montmorillonite	The substance obtained from the zeolitization of silicate. Two tetrahedral silica sheets with a centre octahedral alumina sheet form a laminar structure
Bentonite	Types of clay mineral
Kaolinite	Clay items are made with this material in the ceramics industry. Weathering of feldspar results in this formation. It is incredibly soft, with a hardness of 2–2.5, and comes in white, pink, or grey with a white streak. The chemical make-up is alum $Al_2Si_2O_5(OH)_4$
Peat	Botanical substance that is renewable, natural, and organic. It is a layer of dead organic (non-biomass) material that has accumulated over a longer period of time than usual. Mire types include Blanket, Raised, Fen, Swamp, and Lake
Cocoa shell	A by-product from agriculture industries
Activated alumina	Activated alumina is a porous and highly adsorptive filter medium created by processing aluminium ore. Excess fluoride, arsenic, and selenium are among the pollutants that activated alumina will remove. To stay effective, the medium must be cleaned on a regular basis with an appropriate regenerant such as alum or acid
MSW ash	Ash made from municipal solid waste ash that has been incinerated

investigation at a higher concentration due to the presence of cooperative adsorption or the competing action of other solutes.

Domestic and municipal solid trash is currently disposed of at approved dumping grounds in developing nations (including Malaysia), by either controlled tipping or open dumping. To now, there are just a few well-engineered landfills available. The majority of landfills lack leachate treatment systems. The leachate from this poorly planned landfill has the potential to contaminate our ecosystem, particularly surface and groundwater. Some of the criteria of concern in landfill leachate include ammoniacal nitrogen, heavy metals, colour, and COD.

Aziz et al. [94] have been conducted to treat iron (Fe) in semi-aerobic leachate Pulau Burung Landfill Site (APLS) in Pulau Pinang, Malaysia. The level of Fe was relatively high (close to 10 mg/L). Limestone chip was used in a filter medium as is a relatively inexpensive material in Malaysia (USD10 per metric tonne). A batch equilibrium test was conducted to evaluate the Fe isotherms, followed by a continuous flow filtration column which determines the breakthrough time. The limestone media used in the experiment have a $CaCO_3$ content of over 90% and particle sizes of 2–4 mm. At the landfill, four filter columns (each 150 mm in diameter and

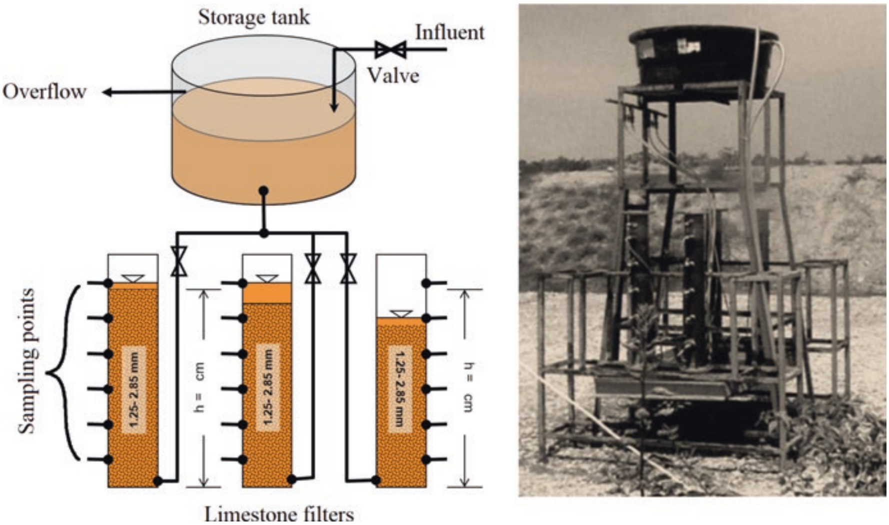


Fig. 8.18 Set up of the filtration column [94]

Table 8.8 Data from Fe Freundlich's isotherm [94]

Mass of limestone in solution, *m* (g)	Initial Fe concentration, C_o (mg/L)	Equilibrium concentration of adsorbate in solution, C_e (mg/L)	$x = C_o - C_e$ (mg/L)	x/m (g/g)
108.238	82	72	10	0.0000924
216.477	82	69	13	0.0000601
324.715	82	65.1	16.9	0.0000520
432.953	82	59.8	22.2	0.0000513
541.192	82	59.9	22.1	0.0000408
649.430	82	58.9	23.1	0.0000408
757.668	82	56.6	25.4	0.0000356
865.907	82	55.8	26.2	0.0000303

1000 mm in depth) were installed (Fig. 8.18). The metal loadings were kept below 0.5 kg/m^3.day for the duration of the experiment, which lasted 30 days. Table 8.8 and Fig. 8.19 show the Fe isotherm data.

According to the results of the column study, 90% of Fe could be recovered from the leachate with a retention period of 57.8 min and a surface loading of 12.2 m^3/m^2 day (Figs. 8.20 and 8.21).

Example:

Determine the breakthrough time for a limestone filter with a 500 m^3/m^2 day filtering rate. The filter column has a surface area of 4 m^2, a depth of 2 m, and the media adsorption data as shown in Table 8.8 and Fig. 8.18. The influent Fe concentration is 82 mg/L, with a breakthrough Fe of 5 mg/L. The limestone used in the

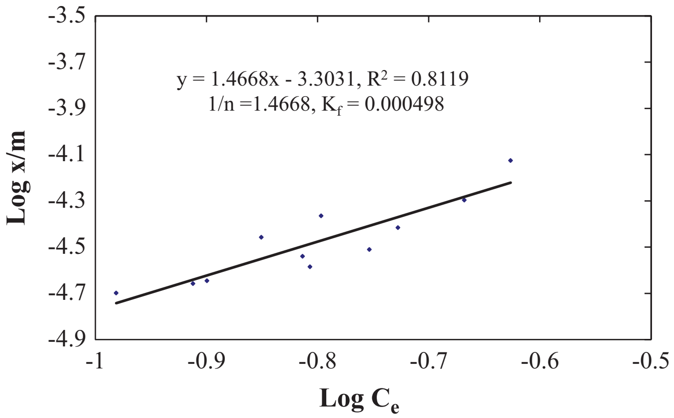


Fig. 8.19 Fe removal from leachate: Freundlich isotherm [94]

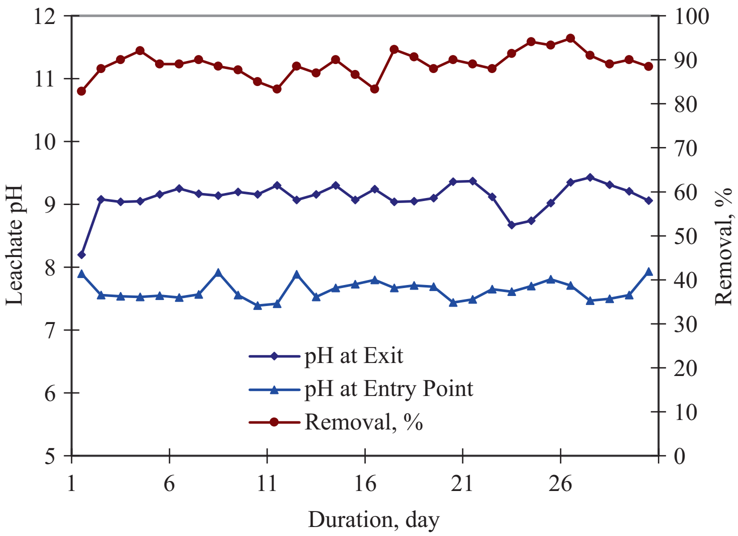


Fig. 8.20 Filtration experiment results for the first 30 days at a surface loading rate of 12.2 $m^3/m^2/$day, metals loading of 0.5 kg metals/m^3/day, filter depth 1000 mm, and particle size 2–4 mm [94]

filter column has a density of 2500 kg/m^3. The batch adsorption studies employed 1 L of liquid leachate [94].

Solution:

1. Plot the Freundlich isotherm using the above data.

   The plots of Freundlich's isotherm are shown in Fig. 8.19, indicating that the coefficient of determination, R-squared, is 0.8119.
2. Determine the adsorption isotherms' coefficients.

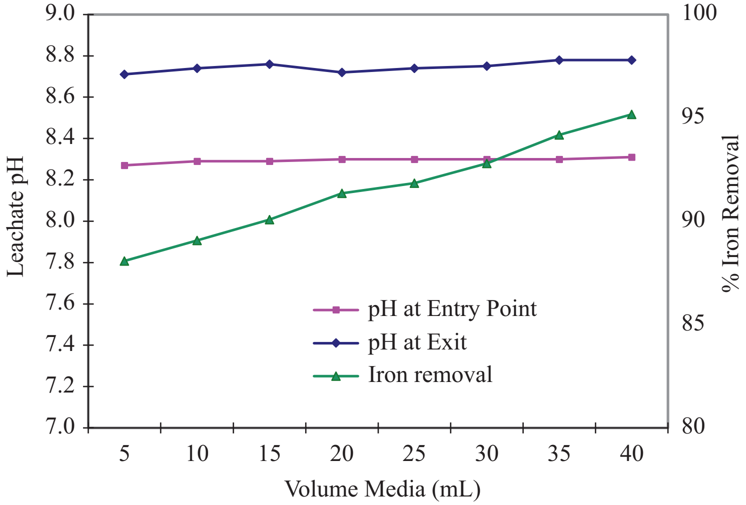


Fig. 8.21 Plot of media volume vs. leachate pH and Fe removal percentage [94]

From Freundlich's equation (Eq. (8.14)):

$$\log \frac{x}{m} = \log k_f + \frac{1}{n} \log C_e \tag{8.14}$$

The two unknown (1/*n*) and k_f can be solved using the above equation.
When $C_e = 1.0$, $\log C_e = 0$, so $\log (x/m)$ equals to $\log k_f$ or $(x/m) = k_f$.
x/m is read from the plot at $C_e = 1.0$.
When $(x/m) = 1.0$, $\log (x/m) = 0$, so $\log (k_f)$ equals to minus $\log (1/n)$.
C_e is read from the plot at $(x/m) = 1.0$.
The original Freundlich's equation is then replaced with these two values.
The plot can also be used to determine the above 1/*n* and *kf* values.
1/*n* is the slope = 1.4668 in the above plot, and *kf* is the antilog of (−3.3031) = 0.000498.
Hence, Eq. (8.14) can be rewritten into Eq. (8.15):

$$\frac{x}{m} = 0.000498 C_e^{1.4668} \tag{8.15}$$

3. Calculate the theoretical capacity (*x*/*m*) o at a Fe concentration of 82 mg/L in the influent.

$$(x/m)_o = 0.000498(82)^{1.4668}$$
$$= 0.319456 \text{mg/mg, say } 0.32 \text{mg/mg}$$

4. Determine the breakthrough time using Eq. (8.16).

$$t_b = \frac{(x/m)_b\, Mc}{(Q)(C_i - C_b/2)} \tag{8.16}$$

Assume that $(x/m)_b = 50\%$ of $(x/m)_o$,

$$\begin{aligned}(x/m)_b &= 0.5(0.32\,\text{mg/mg})\\ &= 0.16\,\text{mg/mg}\end{aligned}$$

$$Q = 500\,\text{m}^3/\text{day}$$

$$\text{Surface area} = 4\,\text{m}^2$$

$$\text{Depth} = 2\,\text{m}$$

$$C_i = 82\,\text{mg/L}$$

$$C_b = 5\,\text{mg/L}$$

$$\begin{aligned}\text{Volume of media} &= (4\,\text{m}^2)(2\,\text{m})\\ &= 8\,\text{m}^3\end{aligned}$$

$$\begin{aligned}M_c &= \rho(\text{volume})\\ &= (2500\,\text{kg/m}^3)(8\,\text{m}^3)\\ &= 20{,}000\,\text{kg}\end{aligned}$$

$$t_b = \frac{(0.16\ \text{mg/mg})(20{,}000\ \text{kg})}{(500\ \text{m}^3/\text{day})(82.5/2\ \text{mg/L})(1/1000\ \text{kg/m}^3)}$$

$$t_b = 8\,\text{days}$$

The feasibility of activated carbon, limestone, and a combination of the two materials as a filtering media capable of attenuating colour, which is found in significant quantities (between 3000 and 4000 PtCo) at one of Malaysia's landfill sites, was investigated by Lau et al. [100]. The study found that utilizing limestone in quantities greater than 20 mL, more than 80% of colour with intensities up to 4000 PtCo could be eliminated (equivalent to 56 g). The adsorption phenomenon has aided the elimination process 3156 m^3 of leachate can be treated for 32 days with a leachate flow rate of 100 m^3/day and a filter bed of 2.25 m^2 and 2 m depth. The daily consumption rate of media is approximately 33 kg or 3.3 kg/m^3 [100].

8.7.5 Evaporation

Evaporation is one of the rising procedures for leachate treatment, which utilizes natural phenomena like wind speed and temperature or relative humidity. Evaporation results in a solid concentrate after elimination of liquid fraction from landfill leachate. Because of implementing natural climatic conditions, the operating cost of this method is very nominal, and no chemical compounds are involved with this method as well. Therefore, this method has already been applied as an alternative or parallel process of the traditional method, and the climatic conditions are found the key influential factors over the effectiveness of this method. Two types of evaporation processes are applicable for leachate treatment, i.e. solar or natural evaporation and mechanical evaporation.

These treatments used the method of heating the leachate to evaporate the water and leave the residue/concentrated leachate. Organic and inorganic substances are commonly found in concentrated leachate, which can be disposed of without or with treatment at landfill sites. Some researchers have looked at this type of treatment system for lowering the volume of leachate as well as for final leachate treatment [101]. However, these treatment approaches are only used as a last resort in the treatment of leachate. To test the full-scale operation of this evaporation and vaporization system, only hazardous waste leachate was used [91].

The distillate can be recovered for water use in these operations, while the remainder is disposed of in the landfill. There will be no inorganic compounds or heavy metals in the distillate. DiPalma et al. [101] were able to extract a distillate volume of approximately 70–75% of the initial leachate sample, but with a TOC value of about 70 mg/L. The presence of organic components in the distillate increased the TOC value. As a result, the distillate must be further processed because leachate evaporation produced rapid stripping of a volatile organic component, resulting in a high TOC concentration in the distillate. Vaporization plant effluents, according to Ehrig [91], are volatile and can contain chlorinated organics and ammonium, necessitating further treatment. Evaporation and vaporization treatment are not always perfect since certain impurities remain in the residual, making it impossible to generate a completely clean distillate. Apart from that, incrustation, foaming, and corrosion concerns have been seen in small-scale tests with municipal waste leachate [91].

8.7.5.1 Solar/Natural Evaporator

The process that applies sunlight heat, wind energy, or relative humidity for leachate treatment is known as solar or natural evaporation. Leachate passes to the nearby collection pond, which is constructed accordingly for the natural evaporation process (Fig. 8.22). Artificial bed lining is provided to prevent the leachate percolation towards groundwater or subsoil. A blended impact of wind energy, solar heat, and relative humidity endorse natural evaporation of leachate and offer almost zero

Fig. 8.22 Natural evaporation pond

liquid discharge leaving concentrated solid residue at the pond bed. The lower relative humidity or dry air is more advantageous for natural evaporation, and wind energy increases the evaporation rate through vapour transportation. The evaporation rate decreases remarkably during the rainy season because of higher relative humidity. However, the natural evaporation method faces a lower rate in such regions globally with unfavourable climatic conditions. Besides unfavourable climatic conditions, two more disadvantageous issues of this method are the requirement of large area and long time for evaporation. So, researches are going on to overcome these shortcomings and enhance the evaporation rate within the reduced land area and shorter time [102]. Panel evaporation for leachate treatment is a recently applied approach to increase the rate of evaporation during the rainy season [103].

8.7.5.2 Mechanical Evaporator

Mechanical evaporation can also be applicable for leachate treatment with necessary unit operations besides natural evaporation [104]. The good quality final effluent with minimum pollutant concentration is the advantageous issue of mechanical evaporation. Vacuum evaporation is the most commonly applied mechanical evaporation system. The leachate characteristics are the vital factor for designing vacuum

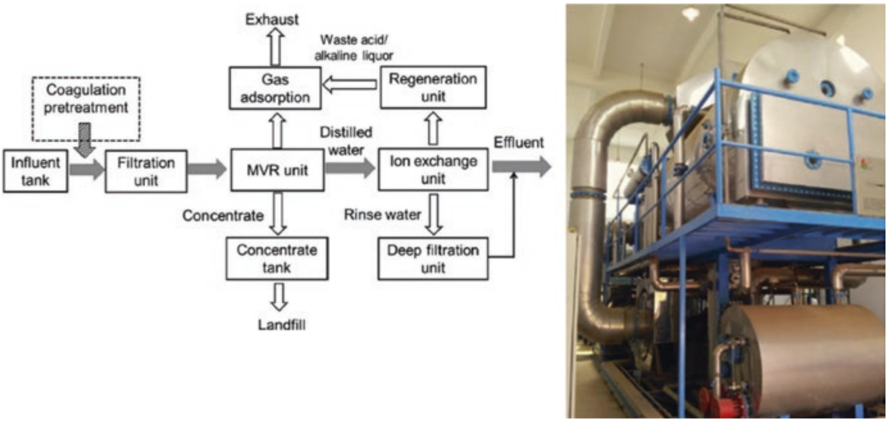


Fig. 8.23 Landfill leachate evaporation system by mechanical vapour recompression (MVR) [104]

evaporation with optimum treatment conditions. Lower pH or acidic environment is more effective for the pollutant removal from leachate containing less volatile organic acids, and pH adjustment influences the liquid–vapour equilibrium for the treatment method. The related factors for vacuum evaporation are pressure, temperature range, liquid-vapour fraction, etc.

Generally, the evaporation rate increases with increasing temperature, but the range remains below the boiling point of leachate. The steam pressure should also remain within a reasonable temperature limit for effective conversion of the vaporization to condensation. Although high-quality effluent is produced through mechanical evaporation, this process requires more energy, which eventually causes a higher operating cost. Application of force evaporation through heating and utilizing thermal energy from methane gas is one of the improved mechanical processes. The research work confirmed that pH adjustment could optimize the pollutants removal through this method since higher pH removes COD and TOC better, while acidic pH enhances the ammonia removal. An example of this mechanical evaporator is shown in Fig. 8.23.

8.7.6 Ultrasound

Gonze et al. [105] looked into using high-frequency ultrasound or ultrasonic irradiation as a posttreatment for biologically pretreated landfill leachate, and the process is very similar to other oxidation processes that generate radical OH. However, ultrasonic produces a large number of by-products, making it difficult to identify them all and maintain the mass balance of the process. Despite a significant delay in removal during sonification, the procedure improves leachate biodegradability (as measured by the BOD_5/COD ratio) to 0.14 with 70% COD removal and a slight increase in BOD_5 at 80 GJ/m^3 with a slight rise in BOD_5. The increase in BOD value could be attributed to the creation of biodegradable species as an intermediary from non-biodegradable organic contaminants rather than being completely converted to CO_2.

In terms of toxicity, the leachate recovered to its initial non-toxic value after sonification at 20 GJ/m^3, indicating the creation of a hazardous intermediate. Ultrasound is frequently used in conjunction with other treatment methods. Joshi and Gogate [106], for example, looked into the treatment of landfill leachate using various ultrasonic reactor configurations combined with advanced oxidation processes. They concluded that the most viable approach for leachate treatment is an ultrasonic flow cell with Fenton, which yielded a maximum COD removal of 92% and increased biodegradability from 0.36 to 0.55. The ultrasonic and Fenton treatments cost 28.7 and 25 US$/$m^3$, respectively.

8.7.7 Irradiation

In this oxidation process, gamma-ray and high-energy electron radiation are used to neutralize humic acid in landfill leachate [107, 108]. The pH value and radiation dose in this process determine the oxidation efficiency of the treated leachate. The electron beam radiation procedure was able to remove 20.7% of DOC (dissolved organic carbon), remove a significant amount of colour, and increase BOD by a factor of six. Despite the fact that the BOD value was increased, Bae et al. [107] and Yamazaki et al. [108] discovered that the procedure converted biodegradable compounds into non-biodegradable compounds, resulting in an acidic by-product. This revealed that by producing radical species, the irradiation technique produced an unselective reaction. As a result, prior to treatment, biological treatment of the leachate is required to remove the biodegradable chemical. Similar to other oxidation processes, the acidic condition was preferred for the generation of radical species in this process, and it was also influenced by radiation exposure. The proportion of the low molecular molecule was proportional to the dosages in a process capable of breaking down a large molecular component into smaller ones.

8.7.8 Membrane Filtration

Membrane filtration is a state-of-the-art approach to landfill leachate treatment, especially stabilized leachate with high dissolved organic matter (DOM). Because of the effectiveness of matured leachate treatment, numerous researches have been conducted on membrane filtration. Membranes are defined as thin barriers with the required pore size and can resist the movement of selective pollutants of fluids. Membrane filtration is a proven technique for landfill leachate treatment and is effectively used in the whole world. Several types of membrane filtrations are commonly used like microfiltration, ultrafiltration, nanofiltration, and reverse osmosis.

Membrane procedures create a selective barrier between two liquids by using a thin film (membrane). The membrane process divides the influent into two streams: permeate (material that passes through the membrane) and retentate (nonpermeating species or retention/rejection species) by applying driving pressure across the membrane. Membrane removal capabilities are measured in terms of permeate flux and selective removal, which are primarily determined by the components in the two streams as well as the driving pressure used. The pore size or particle size cutoff of the membrane used in the process, as shown in Table 8.9, and the operating pressure, as shown in Fig. 8.24, can be used to classify it.

The pores in the UF membrane are substantially larger than those in the NF and RO membranes, but the pressure is lower as a result. UF is typically used to separate small particles, colloidal, and macromolecular organics, whereas RO is mostly utilized to remove dissolved compounds due to the wide membrane hole sizes involved. Due to the sieving action, MF and UF membranes are also capable of segregating smaller sizes of particles due to their bigger pores. NF and RO, on the other hand,

Table 8.9 Classification of membrane processes [109, 110]

Membrane	Pressure applied	Pores sizes	Material separated
Microfiltration (MF)	50–500 kPa	0.05–1.5	Microbial cells, large colloids, small particles
Ultrafiltration (UF)	50–500 kPa	0.002–0.05	Macromolecules, viruses, colloids
Reverse osmosis (RO)	5–8 MPa	0.0001–0.0003	Aqueous salts, metal ions
Nanofiltration (NF)	0.5–1.5 MPa	0.0005–0.007	Viruses, humic acids, organic molecules, Ca^{2+}, Mg^{2+}

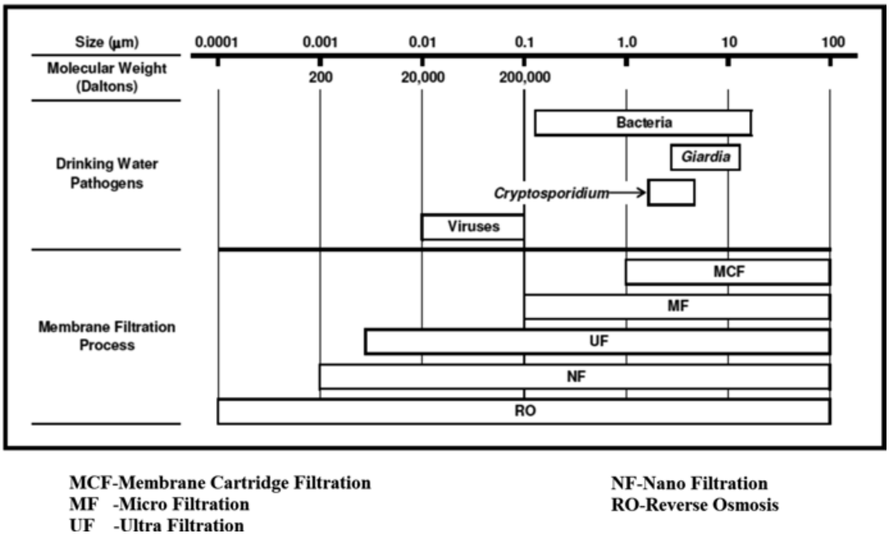


Fig. 8.24 Different types of filtration [111]

can remove contaminants for both organic molecules and inorganic ions by sieving and diffusion-controlled transport (induced by a change in osmotic pressure). Organics and most inorganic salts can be removed almost completely by RO. The nature of the water determines NF removal for inorganic compounds, but bivalent ion removal is much more than monovalent ion removal. As a result, contaminant removal via membrane processes is influenced by the size, shape, and charge of pollutants as well as pore diameters. Tubular, capillary, hollow fibre, spirally wound sheet, plate, or frame membranes are now available as modules or cartridges, ready to use. Tubular modules were favoured by some membrane processes for ease of cleaning, whereas spiral wound modules were selected by others for more effective flux.

Membrane methods, which can remove a wide range of contaminants, including humic acid and inorganic ions, have been a very promising alternative to other conventional treatment processes for the user in leachate treatment. Membranes are also used to fractionate organic pollutants to determine their molecular mass, which provides useful information on the compounds' recalcitrance in the leachate as well as the efficacy of specific treatment techniques on the compounds. Membrane fouling, on the other hand, continues to be a major impediment to the use of membrane processes due to the resulting decrease in membrane specific flow. A fouling layer gradually accumulates on the membrane surface, causing it to fail. The buildup can be caused by colloidal particles, iron and manganese oxides, biofilm, and inorganic forms. Fouling of membranes can be avoided by using a 'cross-flow' system rather than a 'dead-end' system because the flow of water can pull back the chemicals deposited at the membrane layer. Fluid management in the membrane unit can also be used to re-entrain the colloid layer by creating a turbulent flow regime that is unstable and erratic. Pretreatment of the influent with coagulation and filtration can also significantly reduce fouling. Meanwhile, inorganic scaling can be prevented by adding a chemical that ensures the solubilities of the scaling ions are not exceeded. A few membrane process modules for treating leachate while also preventing fouling on the membrane layer has recently been introduced to the market.

8.7.8.1 Microfiltration (MF)

The MF membrane is a porous membrane with the largest pore diameters of any membrane process, and it is primarily employed in the treatment system to separate microparticles (clarification). MF membranes cannot efficiently treat highly contaminated wastewater such as landfill leachate since their removal method is solely based on particle screening. Bacteria and chemicals like humic acid, as well as inorganic ions, are not removed by the MF membrane processes. Microfiltration is a physical treatment method of landfill leachate, which apply a definite pore-sized membrane to separate suspended particles and microorganisms from a contaminated fluid. Generally, pore size 0.1–5 μm membrane filters are used in MF to separate large colloids and small particles. MF is a low-pressure filtration method that uses less energy and is less costly. The MF can fairly remove bacteria and suspended particles, but this method is not applicable for a long time since fouling causes the gradual deterioration of membrane surface. Because of membrane fouling and flux reduction, this method cannot be applied as a sole treatment method. Practically, the implementation of MF is appropriate for pretreatment, parallel treatment, or posttreatment with biological and chemical treatment processes as a hybrid approach.

8.7.8.2 Ultrafiltration (UF)

Ultrafiltration (UF) is an efficient variety of membrane filtration, which potentially eliminates the macromolecules (10^3–10^6 Da), specifically protein from landfill leachate applying pressure or concentration gradients through a semipermeable membrane. UF can resist the high molecular weight solutes and suspended solids, while solutes of low molecular weight and water pass through the membrane. UF is a dead-end filtration system that applies molecular weight cut-off (MWCO) membranes. Basically, UF is used before RO and NF combination or as a part of any blended treatment method like biological treatment -UF- coagulation or activated sludge-UF-RO. Even though UF can minimize the fouling impact of the RO process (smaller pore filtration), but fouling is a disadvantage of UF itself. So, the shearing rate needs to be applied continuously to mitigate the fouling impact.

The porous membrane to which UF belongs can separate smaller particle components from MF. UF, which can provide high-quality water in terms of suspended particles, has been used for direct filtration or biologically treated fluids to replace sedimentation and improve quality. Traditional tubular UF systems with flow rates of around 4 m/s typically consume around 10 kWh/m^3 permeate [112]. Because it can prevent fouling on subsequent treatment systems and can also be used in conjunction with other treatment procedures, UF has primarily been studied as a pretreatment system for RO and UF [92, 112–114]. High-strength leachate treated with UF was able to retentate 99% inorganic, organic compounds without impeding the organic carbon passage or lowering the pressure (lower flux) [114]. According to the study, the aromatic polymer membrane has the highest flow rate for leachate treatment. Ozturk et al. [66] discovered that using a spiral UF module at 4 bars and a permeate flux of 32 L/m^2 h, they were able to remove roughly 77%, 80%, and 7% of COD, colour, and conductivity, respectively.

8.7.8.3 Nanofiltration (NF)

Nanofiltration (NF) is a pressurized process of filtration that falls between RO and UF concerning its particles (molecular or ionic) resisting capability. NF method provides an all-around approach to meeting several quality parameters like removal of microbial contaminants, inorganic or organic pollutants, and heavy metals from leachate. Usually, NF is weak for resisting sodium and chloride, but it can effectively resist dissolved organics or sulphate ions from leachate. Dense or porous, and ceramic or organic membranes can be used in NF technology. The effectiveness of NF technology is strongly correlated with diffusion coefficient, charge valency, energy for hydration and solute type. The pH adjustment is a critical factor regarding membrane charge since it is merely influential on resisting capacity [78]. The reduction in concentrate volume during this process is due to a low rejection rate for sodium and chloride and a high rejection rate for dissolved organics and sulphate. Most of the multivalent heavy metal cations are rejected through this process, while harmless monovalent cations pass through the membrane. However, according to the studies, higher (about 85%) rejection of conductivity, suspended solids, COD, and heavy metals, as well as a lower rate of ammonia nitrogen (20%) and nitrate (45.5%) are observed through NF [27]. The process efficiency of NF improves with the combination of physicochemical or biological treatment. A combination of electrocoagulation and NF resulted in 80% turbidity and 67% TOC removal from stabilized leachate [79], but membrane fouling reduces the efficiency of NF as well.

The NF technique is also known as low-pressure reverse osmosis because of its selectivity in removing ions from wastewater due to differences in osmotic pressures. For organic molecules and inorganic ions, the NF process, like RO, can remove contaminants through sieving and diffusion-controlled transport. Because NF structure is looser than RO's, it can remove impurities from molecules ranging in size from 200 to 300 g/mole, allowing for higher flux and lower operating pressure than RO [67]. NF also allows for the removal of ions due to electrostatic interactions between the ions and the NF membranes. Electrostatic interactions occur because most NF membranes are thin-film composite membranes made up of hydrophobic polymers with a negatively charged group. The NF method has been focused on leachate treatment studies because of its capabilities, which are essentially identical to RO and can be applied at lower operating pressure [26, 67, 112, 115–117].

With its negatively charged membranes, the NF membrane can separate organic substances from various types of salts, as well as separate different types of salts (both anions and cations) at a faster rate than the RO membrane. The charged membranes caused anion repulsion, which governs the solute retention for specific salts. Retention of anion with higher valency is reduced due to increased membrane repulsion towards the anion. Sulphate (SO_4^{2-}) retention, for example, is significantly higher than chloride (Cl^-) retention [116].

Linde and Jonsson [116] demonstrated that at low salt concentrations, NF rejection for sulphate salts was 88–96%, whereas NF rejection for chloride salts was only 12–47%, owing to the differential in charge density of the anions. Rautenbach et al. [112] found rejection rates of roughly 50% for chlorides and nitrate and 96–98% for sulphate. Linde and Jonsson [116] found that divalent cations retained three times more than monovalent cations in their experiments. In their experiments of two distinct NF membranes for leachate treatment, Trebouet et al. [115] found the same elimination trend. Bivalent ions, on the other hand, are rejected more readily by both membranes than monovalent ions. The Donnan effect was used to explain the rejection of mono and bivalent anions: chlorides are driven into the permeate in a multicomponent system, including additional sulphate and chlorides ions [112, 116].

Since the rejections were due to the necessity of electroneutrality, cation rejection across the membranes followed the same pattern. The elimination selectivity of NF membranes made it a very viable alternative for the leachate treatment process because hazardous heavy metals in leachate normally exist as multivalent ions, while other relatively safe elements (potassium and sodium) exist as monovalent ions. According to Linde and Jonsson [116], Cd, Zn, Pb, and Cr were removed at a rate of more than 70%, but Ca and Mg were removed at a rate of less than 10%. However, when compared to the RO method, metal removal was significantly lower.

Low monovalent ion rejection also contributes to the flux permeate, which was many times higher than that of a RO membrane, with 50 L/m^2 h at 3 MPa and 25 °C for a leachate conductivity of 6800 mS/m at 3 MPa and 25 °C. The removal of TOC by the NF method was also relatively low, with only about 55% of it removed. According to Marttinen et al. [67], ammoniacal nitrogen was removed at a rate of 27–50%, implying that the ammonium in the treated leachate is in the form of an ammonium salt complex. The amount of ammonium salts retained by NF is proportional to the size of the complex, as Awadalla et al. [118] discovered that only 55–98% ammonium sulphate was eliminated. The NF process is capable of effectively removing pollutants in terms of dissolved solids and other characteristics, leaving only clear and colourless permeate. Trebouet et al. [115] achieved a total dissolved solids removal rate of more than 99% and more than 70% for organics, COD, and BOD_5.

The NF process, on the other hand, is highly reliant on the pH of the leachate because it affects the charge of the membrane and humic compounds. When pH drops, the NF membrane's surface charge becomes less negative, and most humic compounds (containing phenolic and carboxylic groups) lose charge. As a result, despite its slightly negative charge, the NF membrane preferred a pH greater than 4, and a pH of 7.5 is the best condition for treating raw leachate in terms of fouling and membrane retention [115]. The ambient temperature has a significant impact on membrane permeability, which affects the NF process. The temperature was found to reduce permeate flux by 30% and 40% when temperatures were dropped from 25 to 10 °C and 25 to 5 °C, respectively [67].

Rochem Company's NF modules have also been used to investigate the NF/crystallization system [112]. The modules were chosen for their fouling resistance and crystal content, which will be used to treat the RO system's concentrate stream. The module was built by stacking rectangular membrane cushions and spacer plates in a specific order to avoid stationary areas and reduce internal friction losses. The UF modules were tested to handle around 4 m^3/h concentrates from the RO system by putting 32 UF modules inside four NF stage blocks at the Ihlenberg landfill site. At a permeate flux of 3.6 m^3/h and pressures ranging from 20 to 40 bars, it was able to remove 92–95% sulphate, 20–30% conductivity, and unexpectedly high removal of both COD (92%) and NH_3/NH_4+ (40%). The modules were cleaned by supplying a 30 s zero pressure difference per hour and alkaline cleaning every 250–300 h.

8.7.8.4 Reverse Osmosis (RO)

Reverse osmosis (RO) is a treatment method that can remove unnecessary particles, ions with other pollutants effectively from leachate through a partially permeable membrane by applying high pressure. This pressure is applied to overwhelm the osmotic pressure. RO is highly capable of removing heavy metal concentrations along with other suspended and dissolved molecules. Usually, RO is applied as a posttreatment option of biological or physicochemical treatment to improve the subsequent effluent grade to meet the discharge standard. RO applies solvent diffusion across either a nonporous or 0.001 μm pore size membrane. The differences in diffusivity or solubility are the principal removal mechanism, and it depends on solute concentration or pressure. The research reported significant removal of COD (97%), BOD (60%), turbidity (80%), but insignificant removal of total nitrogen through applying RO [80]. The research also confirmed the linear relation of COD removal with operating pressure. However, the RO process is recognized as the most efficient in COD removal in comparison with other physicochemical methods for leachate treatment. RO employs a semi-permeable membrane as a barrier between two solutions of varying concentrations. After that, osmotic pressure is created between the two solutions, and separation is completed by applying a pressure greater than the osmotic pressure, allowing only the solvent to pass through the membrane. Using a screening mechanism, the RO process also eliminates virtually all compounds with a molecular mass of around 150 kg/kmol. When using the RO process, which works on the principle of osmotic pressure difference, the high conductivity of leachate is an important factor to consider. The conductivity (dissolved solid) of the leachate, which is linked to the salt content, is a significant metric because of its relationship in determining the osmotic pressure.

The RO system has been used as a leachate treatment and has been studied for its ability to remove both organic matter and inorganic ions [26, 101, 112, 113]. RO has also been used to reduce the volume of leachate by 77–80% and then reintroduce the concentrated leachate into landfills [26]. For the first time, the tubular module RO system was used to treat leachate in 1984. This type of module was chosen because the RO process required an open channel module for effective cleaning reasons due to scale, fouling, and biofouling. A disc-tube module (DT module) was introduced as a leachate treatment option later in 1984, and it has proven to be quite effective. By 1997, this DT module had been installed in more than 75% of leachate treatment plants using the RO process [26].

The RO method can retain 98–99% of both organic and inorganic pollutants, making it ideal for landfill leachate purification [26]. This is consistent with the findings of Chianese et al. [119], who reported 98% heavy metals (Cu, Zn, and Cd) removal in the absence of organic impurities and greater Cu and Zn removal in the presence of organic contamination. This is owing to the fact that these ions form more complexes with organic compounds than Cd, resulting in increased membrane translocation. Despite the fact that the procedure cannot entirely separate all impurities, the permeate from the process will include very low levels of inorganic and organic contaminants.

According to Peters [26], the limit of electric conductivity for a RO treatment plant was between 50,000 and 60,000 S/m. The RO system's effectiveness is demonstrated by full-scale operational plants that use the treatment procedure and have already been used to treat leachate. A plant with a DT module RO system was used to treat 70 m^3/day landfill leachate in Yachiyo Town, Japan. The leachate's conductivity ranges from 237 to 10,000 mS/m. The facility went into service in April 1999 and had been running smoothly for over two and a half years without the need to change any modules. A two-stage RO system with operating pressures ranging from 0.9 to 70.5 MPa and 0.3 to 1.1 MPa was installed at the factory. By lowering the pH to a slightly acidic level and infusing a reagent of organic acid at a concentration of 10–20 mg/L to neutralize all scaling ions, scaling in the plant RO system was avoided. Alkali and organic acids were used to perform chemical cleansing every 1–2 weeks. The RO system removed a significant amount of pollution from high salinity and scaling ions leachate, resulting in potable, high-quality treated water.

Another factory in Ihlenberg, Germany, has been using the same RO system to treat 36 m^3/h since December 1989, with only one membrane change required until 1998 [26]. The system's average salt and organic pollutant removal efficiency was around 99%. Depending on the influent concentration, the plant's working pressure ranged from 36 to 60 bar, and the specific permeate flow was around 15 L/m^2 h. Another treatment plant in Kolenfeld, Germany, which began processing 1.8 m^3/h of leachate in February 1990 and removed over 90% of contaminants, was replaced with a new membrane in April 1993 after more than 3 years of operation [26]. Despite the fact that the leachate has an electric conductivity of 15,000–16,000 S/cm, it was removed at a faster rate.

Because the RO process shows promise in the treatment of leachate, a high-pressure RO system based on a DT module with a 120 bar operating pressure is used to further treat the concentrate [26]. The modules can fire $CaSO_4$ precipitate and even seed nuclei to encourage crystallization. This technique increases permeate recovery from 80% (a concentration factor of 5) to 90% (a concentration factor of 10) for pollutants retained by the membrane [26]. This RO system also increases the capacity of the RO treatment plant to between 100,000 and 120,000 S/m. Controlling crystallization in the process solved both the difficulty of evaporating concentrate and the problem of calcium sulphate solubility [26]. The separated crystal will lower the membrane's scaling potential and may even promote a permeate recovery rate of 95%. The RO process for leachate has proven to be very effective, but it comes at a high cost due to the high operating pressure, chemical cleaning, and chemical addition in the feed to prevent ion scaling.

8.8 Chemical Treatment Technologies

8.8.1 Chemical Precipitation

8.8.1.1 Introduction

Chemical precipitation works by converting leachate contaminants into solid forms that can be easily recovered from water. Lime, alum, ferric sulphate, and ferrous sulphate, when combined with coagulation techniques, are effective at removing a variety of pollutants. The solubility of pollutants in leachate determines how much precipitation is removed. In leachate, heavy metals in the form of cations may precipitate as hydroxide and carbonate solids, for example.

This would promote solid deposition as the process for extracting heavy metals and inorganic materials from leachate or wastewater. Chemical injections react with heavy metal ions to convert them into insoluble precipitates, which remain in dissolved form in the leachate and wastewater. The separated precipitates can be extracted by filtration or sedimentation, and the supernatant effluent can be discharged or reused as required. Hydroxide and sulphide precipitation are two commonly applied chemical precipitation processes, ensure around 95% heavy metal removal efficiency [120]. Heavy metals (Na, K, Ca, Fe) are typically precipitated as hydroxides using chemicals, such as sodium hydroxide (NaOH), quicklime, hydrated lime, and magnesium hydroxide ($Mg\ (OH)_2$). The most commonly used and cheapest form of lime is hydrated lime ($Ca(OH)_2$). Alkali is frequently applied for the solution pH changing where the impact of metallic solubility is negligible [8].

Chemical precipitation of NH_4-N using magnesium ammonium phosphate (MAP), also known as struvite, sedimentation that has been studied and extended to a variety of wastewaters. COD was not substantially decreased by MAP precipitation, implying that a biological treatment mechanism to extract COD could be included. Previous studies reported up to 98% NH_4-N removal (initial concentration was 5618 mg/L) applying chemical precipitation within 15 minutes while maintaining a pH of 8.5–9.0 and resulting in the lowest MAP solubility [4]. Similarly, struvite precipitation was used at a stoichiometric ratio of Mg: NH_4: PO^4_3 = 1:1:1 for anaerobic pretreatment of raw landfill leachate. At a pH of 9.2, with an influent ammonium concentration of 2240 mg/L, maximum ammonia and TKN removal was observed up to 85%, but organic nitrogen removal was not possible. Furthermore, the overall COD elimination figure was about 50%. Chemical precipitation, on the other hand, has long been used to remove heavy metals from aqueous solutions because of its versatility and low initial investment [4]. Chemical precipitation, on the other hand, is most likely used to treat high-concentration wastewater containing heavy metal ions, and it becomes ineffective as the metallic ion concentration drops. Furthermore, chemical precipitation is inefficient in general and can result in a massive amount of sludge that is impossible to handle.

8.8.1.2 MAP Precipitation

Several researchers have recently investigated the use of magnesium ammonium phosphate (MAP) precipitation for leachate treatment, which is a novel advancement in chemical precipitation for leachate treatment [66]. As a magnesium and phosphate source, this technique utilized a combination of compounds supplied to the leachate. The chemicals combine with ammoniacal nitrogen in leachate to generate a magnesium ammonium phosphate (MAP) precipitate, which is formed by a crystallization reaction. At 0°C, MAP precipitate is a white crystalline powder with a poor solubility of 0.023 g/100 mL H_2O [27], but it can be easily extracted from water. A simplified reaction for producing MAP precipitate is as follows:

$$Mg^{2+} + NH_4^{+} + PO_4^{3-} + 6H_2O \leftrightarrow MgNH_4PO_4 \cdot 6H_2O$$

For every gram of NH_4^+-N removed, 17.5 g MAP precipitate will form as sludge [27]. Magnesium chloride ($MgCl_2.6H_2O$), magnesium oxide (MgO), or magnesium sulphate ($MgSO_4$) is used as magnesium sources, while phosphate is obtained from sodium hydrogen phosphate ($Na_2HPO_4\cdot12H_2O$), phosphate acid (H_3PO_4), or calcium hydrogen phosphate ($CaH_2PO_4.H_2O$). $MgCl_2$ is preferred as a magnesium source because it dissolves more quickly in water, resulting in a faster reaction time. Among these chemicals, a mixture of $MgCl_2\cdot6H_2O$ + $Na_2HPO_4\cdot12H_2O$ has the highest efficiency, while $MgSO_4$ + 85% H_3PO_4 has the lowest [121]. This is due to MgO's low solubility, which causes slow dissolution and low MAP precipitate formation. Despite the fact that $MgCl_2\cdot6H_2O$ + $Na_2HPO_4\cdot12H_2O$ has the highest removal, it also produces NaCl, as shown below:

$$MgCl_2 \cdot 6H_2O + NH_4^{+} + Na_2HPO_4 \cdot 12H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O + 2NaCl$$

Theoretically, an equivalent amount of 8.357 NaCl is generated for every 1 g of NH_4^+-N removed. The formation of NaCl during the reaction resulted in the treated leachate having a high salinity and conductivity. This problem can be minimised by combining $MgCl_2\cdot6H_2O$ + $CaH_2PO_4\cdot H_2O$ or $MgSO_4$ + 85% H_3PO_4 because the chemicals only produce $CaSO_4$ (settle down) or H_2O as a by-product with less ammoniacal nitrogen removal. Reaction for a combination of $MgCl_2\cdot6H_2O$ + $CaH_2PO_4\cdot H_2O$ and $MgSO_4$ + 85% H_3PO_4 is as shown below:

$$MgCl_2 \cdot 6H_2O + NH_4^{+} + CaH_2PO_4 \cdot H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O + CaSO_4$$

$$MgSO_4 + NH_4^{+} + H_3PO_4 \rightarrow MgNH_4PO_4 \cdot 6H_2O + H_2O$$

Ozturk et al. [66] and Li et al. [27] found that at a stoichiometric ratio ($Mg:NH_4:PO_4$ = 1:1:1), high ammoniacal nitrogen removal may be accomplished, with maximal removal of roughly 85% and 96%, respectively. Overdosage of Mg^{2+} or PO_4^{3-} up to 10% higher than the stoichiometric ratio will improve ammoniacal nitrogen removal, but dosage beyond that will not result in improved removal efficiency [121]. More ammoniacal nitrogen removal is achieved at a pH range of 8.5–9.0 [115], which is within the lowest pH range for MAP solubility (pH 8–10) [66]. This pH is much lower than what is needed for effective air stripping removal.

The MAP precipitation technique can achieve a reduction of roughly 50% in total COD [66]. This procedure, like the coagulation process, produces considerable volumes of sludge that must be disposed of. The sludge produced by the MAP precipitation process, according to Li et al. [27], has a high sludge density, rapid settling, a high solid content, and is entirely inorganic. Because the sludge is relatively stable and contains a high solid content, it was discovered to be very easy to dispose of, allowing it to be dumped at a landfill without stabilization or dewatering. Li and Zhao [121] investigated the utility of sludge in agricultural applications and discovered that it could be used as a multi-nutrient fertilizer for vegetable growth. Because of its low solubility in water and soil, MAP struvite slowly releases phosphorus, nitrogen, and magnesium, making it a very efficient source of these nutrients. The overdosing of MAP precipitation and heavy metals in the sludge had no effect on vegetable growth; in fact, the increased levels of P and Mg aided it.

Example:

Calculate the daily requirement for $MgCl_2 \cdot 6H_2O$ and $Na_2HPO_4 \cdot 12H_2O$ in combination to treat 600 m^3/day of leachate. Assume that the initial ammoniacal nitrogen concentration in the leachate is 1000 mg/L.

Solution:

The daily amount of ammoniacal nitrogen that must be removed

= Concentration × flow

= 1000 mg/L × 600 m^3/day

= (1000 mg/L × 1000 L/m^3) × 600 m^3/day

= 6.0×10^8 mg

= 6.0×10^5 g

According to the reaction:

$$\underset{1\text{mol}}{\mathrm{MgCl_2}} \cdot 6\mathrm{H_2O} + \underset{1\text{mol}}{NH_4^+} + \underset{1\text{mol}}{Na_2HPO_4} \cdot 12\mathrm{H_2O} \rightarrow \underset{1\text{mol}}{\mathrm{MgNH_4}PO_4} \cdot 6\mathrm{H_2O} + \underset{2\text{mol}}{2\mathrm{NaCl}}$$

$$\begin{pmatrix} \mathrm{N} = 14\mathrm{g/mol}; \mathrm{Mg} = 24\mathrm{g/mol}; \mathrm{Na} = 23\mathrm{g/mol}; \mathrm{H} = 1\mathrm{g/mol}; \\ \mathrm{P} = 31\mathrm{g/mol}; \mathrm{O} = 16\mathrm{g/mol}; \mathrm{Cl} = 35.5\mathrm{g/mol} \end{pmatrix}$$

1 mol NH_4^+ can be removed by 1 mol $Na_2HPO_4 \cdot 12H_2O$ and 1 mol $MgCl_2 \cdot 6H_2O$

$$1\mathrm{mol\,N} = 1\mathrm{mol\,Na_2HPO_4} \cdot 12\mathrm{H_2O\,and\,1mol\,MgCl_2} \cdot 6\mathrm{H_2O}$$

$$14\mathrm{g\,N} = 358\mathrm{g\,Na_2HPO_4} \cdot 12\mathrm{H_2O\,and\,203g\,MgCl_2} \cdot 6\mathrm{H_2O}$$

$$1\mathrm{g\,N} = 25.57\mathrm{g\,Na_2HPO_4} \cdot 12\mathrm{H_2O\,and\,14.5g\,MgCl_2} \cdot 6\mathrm{H_2O}$$

For removal of 6.0×10^5 g N

$$= \left(25.57 \times 6.0 \times 10^5\right) \text{g}\, Na_2HPO_4 \cdot 12\text{H}_2\text{O and} \left(14.5 \times 6.0 \times 10^5\right) \text{g}\, \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$$
$$= 1.5 \times 10^4 \,\text{ton}\, Na_2HPO_4 \cdot 12\text{H}_2\text{O and}\, 8.7 \times 10^3 \,\text{ton}\, \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$$

8.8.2 Chemical Oxidation

The loss of one or more electrons from the oxidized element to an electron acceptor, which is another element, is referred to as oxidation. Chemical substances containing oxygen or oxygen molecules are examples of electron acceptors. These oxidants or electron receivers react with pollutants and mineralize them. Chemical oxidation promotes the conversion of toxins to inorganic substances, water and carbon dioxide, or to convert them to any non-toxic products at least. Ozone, calcium hydrochloride, potassium permanganate, and chlorine are the most common oxidants used in leachate treatment. Oxidants are chemicals that are employed in the oxidation process.

By exchanging electrons between oxidants and chemical species in the leachate, the oxidation process changes the oxidation state of the species. Oxidation reactions are known as reduction-oxidation processes (redox) because one species loses electrons (oxidizes) while the other gains electrons (reduced). Chemical oxidants can be added to the treatment system at different stages, such as as a first-stage therapy, in between treatments, and as a final treatment, which is usually for disinfection. Algae or biological growth management, organic pollution reduction, odour and taste removal, colour removal, metal precipitation, and coagulant aids are all examples of chemical oxidation applications. When compared to other treatment processes, oxidation has the advantage of removing both biodegradable and non-biodegradable substances while producing no sludge or deposit.

The pollutants were either converted entirely to CO_2, H_2O, and salts or transformed into less harmful chemicals. However, oxidation methods are more expensive and technologically complex than traditional treatment processes, resulting in higher treatment system maintenance and reconditioning costs. As oxidants, a variety of common chemicals are used. Some of these include chlorine, calcium hypochlorite, potassium permanganate, hydrogen peroxide, and ozone. Each chemical oxidant has its own set of advantages and disadvantages, as shown in Table 8.10. Chemical oxidants like hydrogen peroxide are weaker oxidants than chlorine and ozone. Chemically unstable, ozone, on the other hand, is far more expensive than chlorine. The oxidant's power is calculated using the electrode potential of a substance, also known as the 'standard electrode potential' (E_o). Table 8.11 lists the standard electrode potentials for various chemical oxidants used in oxidation processes.

Oxidation methods use oxidants to eliminate contaminants through direct and indirect oxidation of the substance during treatment. In the direct oxidation process,

Table 8.10 Leachate treatment survey for coagulation flocculation [122]

Coagulants used	Doses	pH	Parameter measured	% removal	Leachate
$FeCl_3$	1000 mg/L	3	COD and colour	24 and 80	–
	0.035 mol/L	4.9	COD and turbidity	55 and 94	–
	1.5 g/L	6.2	COD	25	Fresh
	1.5 g/L	7.9	COD	75	Stabilized
	650 mg/L	7	COD, SS, and TN	84.6, 92, and 58.7	–
	1–1.5 g/L	5	COD, turbidity, and SS	55, 95, and 83	Stabilized
	900 mg/L	-	COD	60	Stabilized
$AlCl_3$	0.035 mol/L	5.5	COD and turbidity	42 and 87	–
	0.5 g/L	7	COD	31	Fresh
	0.5 g/L	7	COD	56	Stabilized
$Ca(OH)_2$	7 g/L	12	COD	Varying (30–45)	Fresh and partially stabilized
	8 g/L	12	NH_3-N	95	Anaerobically pretreated
$Al_2(SO_4)_3$	50 mg/L	5.5–6	Humic acid	95	Stabilized
	700 mg/L+ 3 mg/L cationic	4.5	COD, TOC, and colour	23, 15, and 70	Old
Polyaluminium chloride (PAC)	360 mg/L	4.5–5.5	Humic acid	95	Stabilized
	800 mg/L	8	COD, SS, and TN	91, 76, and 58.6	–
	200 mg/L+ 100:1 polymer	7.8	COD & colour	65 and 75	–
Electro-coagulation	Fe-Cu electrodes Al-Cu electrodes	–	COD	30–50	Old

contaminants are adsorbed onto the oxidants and eliminated by the oxidant's electron transfer reaction. The production of intermediate free radicals such as O_2, OH, and HO_2, which are involved in the oxidation and degradation of pollutants, results from the indirect oxidation of oxidants. In the oxidation process, the hydroxyl radical (OH) is the most important and reactive of these radicals. The OH free radical has a high oxidation potential ($E_o = 2.80$ V) and can form chains with a wide range of organic molecules. Within a millisecond, the OH free radical can react with organic molecules in an unselective manner, allowing it to remove a wide range of organic substances in a short amount of time. This reactive oxidation technique has

Table 8.11 Chemical oxidant standard electrode potentials [109]

Oxidant	Reduction half-reaction	E, °V
Chlorine	Cl_2 (g) + $2e^- \rightarrow 2Cl^-$	1.36
Oxygen		
Basic	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	1.23
Acidic	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	0.40
Ozone, basic	$O_3 + H_2O \rightarrow O_2 + 2OH^-$	1.24
Ozone, acidic	$O_3 + 2H^+ + 2e^- \rightarrow O_2 + H_2O$	2.07
Hydrogen peroxide		
Basic	$HO_2^- + 2e^- + H_2O \rightarrow 3HO^-$	0.85
Acidic	$H_2O_2 + 2H^+ + 2e^- \rightarrow 2H_2O$	1.78
Permanganate		
Basic	$MnO_4^- + 2H_2O + 3e^- \rightarrow MnO_2 + 4HO^-$	0.58
Acidic	$MnO_4^- + 4H^+ + 3e^- \rightarrow MnO_2 + 2H_2O$	1.68
	$MnO_4^- + 8H^+ + 5e^- \rightarrow Mn^{2+} + 4H_2O$	1.49

the advantage of entirely converting the chemicals in the leachate to CO_2 as well as partially oxidizing refractory components to make them more biodegradable.

Higher concentrations in the leachate should theoretically result in higher degradation of pollutants unless zero-order kinetics was used during the oxidation operations. Most oxidation processes necessitate research on both raw leachate and dilute samples in order to determine the reaction kinetics involved. The oxidation degradation rate becomes independent up to a specific concentration of pollutants in the leachate, and the process kinetic shifts from first to zero order. Raw leachate exhibited a first-order kinetic, but at greater TOC concentrations of more than 200 mg/L, the degradation rate slowed. It could be because there was a large concentration of inorganic species (Cl^-, PO_4^{2-}, and SO_4^{2-}) on the catalyst surface, which clogged the process [81]. The dark reaction has no effect on the increase in BOD levels.

In leachate treatment, oxidation techniques are used to mineralize resistant contaminants, lowering the COD value and increasing the biodegradability of the leachate, allowing it to be treated biologically. The effectiveness of hydroxyl radical oxidation processes is reduced by higher alkalinity, such as bicarbonate and carbonates, which act as hydroxyl radical scavengers. These factors posed some challenges in terms of leachate treatment, as most old leachate has an alkaline pH and significant alkalinity and hardness. Carbonate concentrations in the alkaline portion of the carbonate equilibrium [81] and their effects on the hydroxyl radical are depicted below:

$$CO_2 + H_2O \underset{pK=6.3}{\leftrightarrow} H_2CO_3 \leftrightarrow HCO_3^{-pK=10.2} + H^+ \leftrightarrow CO_3^{2-} + 2H^+$$

$$HO + HCO_3^- \rightarrow OH^- + HCO_3$$

Many studies and experiments have been conducted on the effectiveness of advanced oxidation processes (AOP) for the treatment of leachate. High-frequency ultrasound, UV, ozone, and oxidants with catalysts such as TiO_2/UV, O_3/H_2O_2, O_3/UV, O_3/heterogeneous catalyst, Fenton oxidation (Fe^{2+}/H_2O_2), and even photo-assisted Fenton (Fe^{2+}/H_2O_2/UV) are used in the processes. The efficiency of oxidation procedures as pretreatment and posttreatment processes prior to biological treatment systems is primarily investigated [113].

Chlorination has long been employed as a disinfectant in water treatment. Chlorine interacts with water to produce hypochlorous acid and hypochlorite ions (OCl^-) under normal conditions:

$$Cl_2 + H_2O \leftrightarrow HOCl + H^+ + Cl^-$$

$$HOCl \leftrightarrow H^+ + OCl^-$$

With E_o of 1.49 and 0.90 V, respectively, both of these species have an extremely significant oxidation potential. As a result, chlorine can serve as an oxidizing agent in addition to being a disinfectant. The chlorination method was employed as a tertiary treatment for leachate from the Ampang Jajar Landfill Site in Penang, Malaysia, before it was discharged into a nearby watercourse. To get the best COD elimination, a dose of 900 mg/L chlorine was necessary (about 67%). When compared to alum, which requires just 222 mg/L to remove 76% of COD from the same leachate sample, this is a significant difference. As a result, chlorine treatment for landfill leachate is neither viable nor cost-effective. Chlorination of water containing natural organic matter (NOM) also produces a variety of organohalides, including trihalomethanes (THM) ($CHCl_3$, $CHCl_2Br$, $CHClBr_2$, and $CHBr_3$) and halogenic acids. Because the chlorination by-product is a very hazardous and potentially carcinogenic chemical, it may require additional treatment. The use of oxidants containing other elements rather than oxygen should be avoided to avoid the development of secondary pollutants. When using chlorine as an oxidant in leachate with high levels of NOM and humic acids, the same principle should be applied.

8.8.3 Advanced Oxidation Process (AOP)

In recent years, AOP has been suggested as a viable option for the mineralization of recalcitrant organic compounds of landfill leachate. By enhancing the hydroxyl radicals' generation, AOP improves the chemical oxidation potentials. A small number of oxidants such as hydrogen peroxide (H_2O_2) and ozone (O_3) mainly are effective in the treatment of landfill leachate. Concerns regarding the development of toxic reaction derivatives have restricted the use of some others. Chlorine and chlorine derivatives, for example, cause trihalomethanes to increase with other halogenated compounds.

In addition, most AOP employs a mixture of strong oxidants such as H_2O_2 and O_3 or radiation such as electron beam, ultrasound or ultraviolet (UV) and photo-catalyst or transition metallic ions. However, blended approaches such as the Fenton process with hydrogen peroxide (H_2O_2/Fe^{2+}), O_3 and UV, UV and TiO_2, H_2O_2 and UV, or UV/Fe^{2+} are all widely applied AOP techniques for leachate treatment [8]. The generation of OH radicals, which are reactive species capable of oxidizing halogenated organics and improving the biodegradability of recalcitrant organic pollutants, is described as an example of AOP. Some processes also perform a direct reaction between the oxidant and the contaminants [56]. Many research studies where ozonation was applied as a tertiary treatment process have shown that ozonation removes up to 70% of COD. Organic matter removal efficiencies of around 90% have been recorded using O_3 and H_2O_2 combination as an oxidizing agent, whereas 80% COD and 82% NH_4-N removal have been reported using a combination of persulphate and hydrogen peroxide under optimum operating conditions [123].

Furthermore, it has been reported that 97% and 89% TOC removal with 55% and 57% COD removal, respectively, applying photo-Fenton treatment and UV-H_2O_2 within less than 60 min reaction periods, displaying a higher decomposition capability of these photochemical procedures. A proper application of AOPs involves costly reactants such as H_2O_2 and/or O_3 for leachate treatments, and it is not possible to replace them with more cost-effective treatments such as biological degradation. However, combining AOPs with a biological process reduces the total leachate treatment costs significantly. Furthermore, only wastes with low COD contents (5.0 g/L) can be handled successfully with these methods, as higher COD contents would necessitate the use of unnecessarily costly reactants [123]. These are the remarkable drawbacks of AOP.

8.8.3.1 Ozonation

The removal capabilities of ozonation have been studied as a technique for treating landfill leachate for a long time [65]. Because of its instability, ozone must be produced onsite, most commonly through an electric discharge process in a flowing air or oxygen stream. An ozone destruction unit must be installed to collect escaping gas from the treatment system if ozone is to be used as an oxidant. The following are the reactions that lead to the formation of ozone:

$$O_2 + hv \rightarrow O + O$$

$$O + O_2 \rightarrow O_3$$

The oxidation process can speed up the decomposition of organic molecules in the leachate, but substantial concentrations are needed to achieve total degradation. The ozone decomposition rate for leachate treatment is typically 1.3–1.5 g O_3/g COD. The majority of leachate investigations found that this approach is only moderately successful at removing COD [65, 124–126]. Rivas et al. [124] and Baig et al. [126] got only 30–36% COD conversions for stabilized leachate after 1 h of ozonation. Only at higher concentrations of around 3 g/L O_3 may COD elimination be increased by roughly 50% [65]. According to Imai et al. [86], ozonation resulted in a 72% reduction in COD and no change in BOD_5 levels.

In contrast to COD removal, the ozonation process also effectively removes colour in leachate treatment, just as it does in other wastewater treatments. Silva et al. [65] observed that utilizing 1.5 g/L and 3 g/L ozone dosages, ozonation may efficiently remove around 75% of colour due to the mineralization of colouring compounds in leachate. The ozonation technique was found to be fairly effective at removing organic materials. Even though the ozonation process cannot totally oxidize organic molecules, partial oxidations can break down high molecular mass compounds into smaller ones. Wu et al. [127] demonstrated this behaviour in membrane fractionate investigations, where a 37% share of molecular mass compounds with less than 1000 Da was enhanced to 72% after the ozonation procedure. According to Silva et al. [65], this partial oxidation, which produces lower molecular mass molecules, also contributed to a greater TOC content after the ozonation process. Wu et al. [127] reported a poor TOC removal of around 15%, which they attributed to direct oxidation of organic matter with ozone molecules, which produced aldehydes, ketone, and carboxylic acid instead of CO_2.

When it comes to biodegradability, the ozonation process has the potential to increase the leachate's BOD_5/COD ratio even at low doses. Higher COD elimination, rather than higher BOD readings, is responsible for the rise in the ratio. The amount of RBCOD increased by ozonation, on the other hand, remained relatively low (around 20%), indicating poor biological treatment ability [67]. The ozonation method can double the value of rapidly biodegradable COD (RBCOD) in old leachate but has no effect on biologically processed leachate, according to Marttinen et al. [67]. Wu et al. [127] discovered that ozonation alone could convert around 72% of higher molecular weight organics into lower molecular weight organics. This development is likely to be linked to the improvement of biodegradability.

As a result, the effects of ozonation on toxicity have been shown to vary depending on the kind of organism utilized in the tests and the features of the treated leachate [65]. The creation of the poisonous intermediate chemical induced by partial oxidation in the process causes an increase in toxicity in some circumstances. Furthermore, despite the reduction in COD and ammonia nitrogen following ozonation, Marttinen et al. [67] discovered that the leachate's toxicity increased for several of the organisms studied. The ozonation process was observed to raise the pH of leachate during treatment due to the removal of carbon dioxide and volatile fatty acids [127]. The hydroxyl radical generated during ozonation appears to play a minor role in the elimination of organic molecules from the leachate when compared to other oxidation processes. The discovery was made because the removal effectiveness was the same for different starting pHs (absence/presence of carbonate ions), implying that a component in the leachate has a direct reaction with the ozone molecule.

For mature landfill leachate treatment, Aziz et al. [128] used a combination of ozone and Fenton. However, there are some drawbacks to this method, particularly the need to add iron to the Fenton process, which can result in precipitation and iron residues. Later, Zakaria et al. [129] have reported the optimization performance of

$O_3/ZrCl_4$ by RSM and comparison with the ozonation process alone. The performance of $O_3/ZrCl_4$ on the different types of leachate also showed that $O_3/ZrCl_4$ performed well compared to O_3 alone [130]. In semi-aerobic landfill leachate from the Pulau Burung Landfill Site (PBLS), Pulau Pinang, Malaysia, Abu Amr et al. [131] compared the performance of ozonation alone, ozonation with Fenton, and ozone/persulphate. When compared to ozone/Fenton and ozone/persulphate, the results showed that ozonation alone performed poorly. Enhancing the production of hydroxyl radicals by combining ozonation with potential elements or chemicals is one way to overcome this problem. The production of hydroxyl radicals and the oxidation of organic matter can both be increased by ozonation with catalysts.

Meanwhile, Zakaria et al. [132] investigated the performance of advanced oxidation processes (AOPs) in stabilized landfill leachate from the Alor Pongsu Landfill site (APLS) in Perak, Malaysia, using a combination of ozone (O_3) and zirconium tetrachloride ($ZrCl_4$) as a catalyst. The effect of $O_3/ZrCl_4$ dosage, pH, and contact time was investigated using COD and colour parameters as indicators. The experiment was carried out with a gas flow rate of 1000 mL/min 10% and a temperature of less than 15 °C (Fig. 8.25). The maximum COD and colour removal rates were 88% and 100%, respectively. This result was achieved with a dose of 27 g/m^3 ozone, a pH of 6, a reaction time of 90 min, and a dosage ratio of 1:2. (COD g: $ZrCl_4$ g). The reaction rate constant (k) was 0.2364 min^{-1}, with pseudo-first-order behaviour. As a result of the $O_3/ZrCl_4$ mixture's efficiency in the remediation of stabilized landfill leachate, a new alternative method for industrial leachate treatment has been identified. To determine the maximum operating conditions for this treatment, Zakaria et al. [133] looked at the effectiveness of ozone (O_3) dosage, pH variation, and reaction time during the ozonation process. At an ozone dosage of 31 g/m^3, a

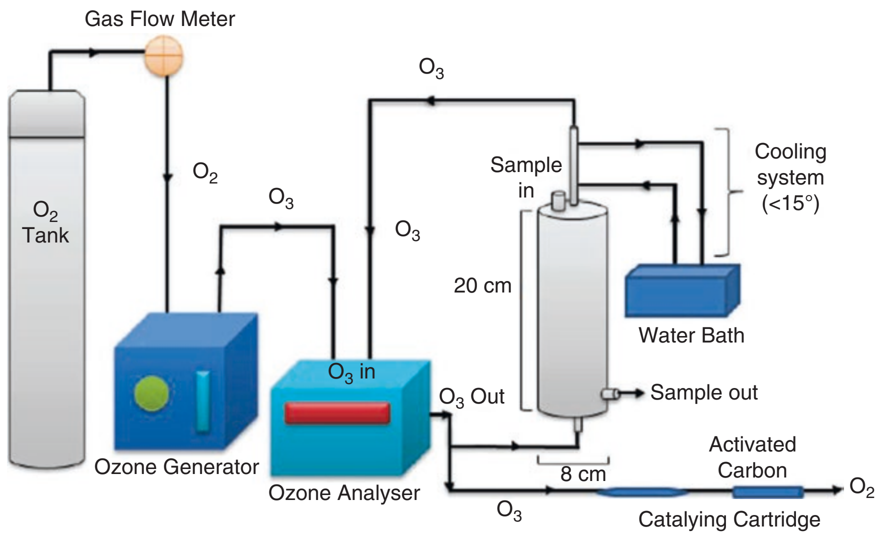


Fig. 8.25 Schematic diagram of ozone equipment and experiment procedures [135]

natural pH of 8.5, and a reaction time of 60 min, the maximum COD removal efficiency was 50%. After treatment with O_3, the biodegradability ratio (BOD_5/COD) improved from 0.08 to 0.23. The ozonation method increased biodegradability and resulted in a high percentage of COD removal. This improvement demonstrated that oxidation has a lot of promise for recalcitrant pollutant wastes like landfill leachate.

8.8.3.2 Photocatalytic Oxidation

Several researchers have looked at a photocatalytic oxidation process that uses the interaction of ultraviolet radiation (UV) and titanium dioxide (TiO_2) to treat landfill leachate. UV radiation is generated using a low-pressure mercury lamp. According to Wang et al. [134], irradiation (313 nm) alone could eliminate around 33% COD and 70% colour. Titanium dioxide is employed in the method because it is a common photocatalyst semiconductor with a large enough band gap energy to allow for redox reactions in the presence of UV light.

The photocatalytic oxidation process is influenced by the photocatalyst concentration, pH value, starting pollutants concentration, and light intensity. Because of its high adsorption capacity on its surface, the semiconductor has the potential to remove pollutants. Because of its adsorption capabilities at pH 3, the new TiO_2 catalyst (Hombikat UV100) can reduce TOC in leachate by up to 68% [81]. The study also discovered that UV-adsorbing aromatics are preferred over aliphatic molecules for TiO_2 adsorption. However, considerable TOC reduction was only achieved at a TiO_2 concentration of roughly 5 g/L, which was determined to be the optimum photocatalyst concentration (Hombikat UV100) in the batch experiment [81]. Due to the use of a catalyst and irradiation during the treatment, photogenerated holes are generated on the catalyst surface, resulting in intermediate free hydroxyl radicals in the presence of O_2 and H_2O. The reaction for forming photogenerated holes in the process, as well as their role in the generation of hydroxyl radicals, is as follows:

$$TiO_2 + hv \rightarrow TiO_2\left(h^+ + e^-\right)$$

$$TiO_2\left(h^+\right) + H_2O \rightarrow TiO_2 + \cdot OH + H^+$$

$$TiO_2\left(h^+\right) + HO^- \rightarrow TiO_2 + \cdot OH$$

The organic component is converted into harmless inorganics such as CO_2, H_2O, and mineral acids by photogenerated holes (direct oxidation) and reactive free radical species (indirect oxidation). The oxidation process is influenced by the amount of O_2 present during illumination, as well as the amount of radiation and TiO_2 concentration utilized. The photocatalyst process for leachate degradation is pH-dependent, and it has been proven to be efficient in the acidic range of pH 3–5 (varies for difference photocatalysts used). In a study of two novel TiO_2 photocatalysts, this tendency was seen (Hombikat UV100 and Degussa P25). For the usage of

Hombikat UV100 as a photocatalyst, Bekbolet et al. [81] discovered an optimum pH of 3; meanwhile, Weichgrebe reported an optimum pH of 5 for Degussa P25 [136]. For COD concentrations up to 700 mg/L [136] and TOC concentrations of 200 mg/L [81], photocatalytic oxidation of leachate followed a first-order kinetic. As a result, larger concentrations would promote photocatalytic degradation of organic compounds up to a certain point, but after that point, the degradation rate would drop, and another effect would take over. This is due to an increase in inorganic ions, including chloride, phosphate, and sulphate, which have been shown to hinder the breakdown process.

Photocatalytic oxidation studies revealed a significant elimination of TOC with a minor rise in BOD [81, 137]. For the photocatalyst procedure, illumination for around 5–10 h can accomplish up to 70–88% TOC removal and less than 60% COD elimination. However, because the catalyst is deactivated, more illumination may not result in an increase in elimination. The component that triggered the deactivation has been the subject of numerous speculations. Deactivation occurs because the photogenerated holes process could not occur, and O_2 could not be adsorbed to the TiO_2 surface due to the adsorbed species on its surface, according to Cho et al. [137].

COD removal cannot be achieved even by replacing the catalyst with a new one; nevertheless, TOC removal can be achieved. Even without irradiation, the removal is due to the adsorption of chemicals on the catalyst surface. Mineralization cannot be achieved with a fresh catalyst due to incomplete mineralization in the prior treatment, which resulted in the creation of non-photocatalyst degradable materials such as SiO_2 compounds. These materials also accumulated on the catalyst's surface. Water washing or sonication can both be used to rejuvenate photocatalysts. In severe temperatures and pressures (5000 Pa to 500 kPa), sonication creates a shock wave and cavitation, which can dislodge adsorbents off the surface. A catalyst regenerated by sonication had a higher removal efficiency than a catalyst regenerated by water washing. The process may also be deactivated by fast recombination of the photogenerated hole, as shown below:

$$TiO_2\left(h^+ + e^-\right) \rightarrow TiO_2 + \text{heat}$$

$$TiO_2\left(e^-\right) + \cdot OH \rightarrow TiO_2 + HO^-$$

Adsorbed components may reduce the active surface on the catalyst, resulting in the deactivation of the photogenerated hole. Aside from that, intense coloured leachate might stymie the process by lowering the amount of irradiation or UV light that reaches the catalyst suspension, therefore interfering with the oxidation process. Bauer et al. [138] proposed a method for immobilizing TiO_2 on quartz glass fibre for a more efficient photocatalyst process by tailoring the intensity of irradiation used to form a photogenerated hole. This technology also eliminates the need for a separation process to remove the catalysts after the treatment. Because trivalent ions can improve quantum efficiency by lowering electron densities in reactive TiO_2, more photogenerated holes can be stimulated during the process by doping TiO_2 with various materials, such as Al. Because complete conversion to CO_2 is achieved, a higher catalyst concentration can prevent a significant amount of intermediate biodegradable species from forming [81].

8.8.3.3 Photochemical Oxidation

To improve the performance of light-induced oxidation processes, researchers used UV light in the presence of oxidants such as ozone, H_2O_2, Fenton reagents, and even a combination of two or more oxidants to investigate photochemical oxidation processes for treating leachate [137–140]. The oxidation efficiency is determined by the concentration of the oxidation reagent and the intensity of radiation energy, in addition to pH, presence of O_2, and organic matter in the leachate that can be completely mineralized into CO_2, H_2O, and salts. For the generation of effective free radicals, the photochemical process, like other oxidation processes, required a low pH. Because it effectively scavenges electrons and changes into numerous oxygen precursor species such as O^{2-}, HO^{2-}, HO_2, and H_2O_2, oxygen plays a significant role in photocatalyst oxidation. Photochemical oxidation tests conducted by Koh et al. [139] revealed a decrease in O_2 level during the process, indicating that photolysis of oxygen occurs, resulting in the generation of active neutral O_2/O_3 radicals and O_2/O_3 anions. In the presence of oxygen, COD removal efficiency was higher than in the absence of oxygen [139].

Since the production of hydroxyl radicals can be done by direct photolysis of hydrogen peroxide, a UV/H_2O_2 combination has been devised. However, using short-wave UV irradiation (254 nm) rather than irradiation near the UV area, which has little adsorption on the molecules, is more efficient for the photolysis of H_2O_2 [138]. With the use of a low-pressure mercury lamp, Koh et al. [139] were able to achieve optimum UV/H_2O_2 elimination (254 nm). After an 8-hour reaction employing various UV sources, photochemical processes using UV/H_2O_2 may successfully remove 40–64% COD and 38–59% AOX with a little increase in BOD. Wenzel et al. [140] achieved a TOC degradation of roughly 89% at a similar reaction period, but no substantial reduction of TOC was accomplished utilizing only each component separately.

The use of a combination of ozone and other oxidants has been studied to see if it can improve the technique's ability to promote free radical production and organic contaminant mineralization. According to Wu et al. [127], the oxidation state (measured by mean oxidation number of carbon, or MOC) of O_3 combinations with UV or hydrogen peroxides only increases up to the ozone dosage of around 0.6 g/L before stabilizing. In a mixture of O_3/H_2O_2, photolysis of H_2O_2 and ozone breakdown, which resulted in the synthesis of hydrogen peroxide and its deprotonated form (peroxyl anion), were key contributors to the generation of the hydroxyl radical [140]. The use of foam suppressants such as sulphuric acid in the system was also discovered to cause intense foaming in the bubble column when a mixture of O_3/H_2O_2 was used. Catalase can be used to remove any leftover H_2O_2 following the treatment.

Wu et al. [127] demonstrated that all three forms of photochemical AOP (O_3, O_3/H_2O_2, and O_3/UV) could boost the biodegradability of leachate, resulting in a BOD_5/

COD rise from 0.06 to 0.5 mg/L at a 1.2 g/L ozone dosage. Combinations of O_3/UV and O_3/H_2O_2 were similarly successful in removing 90% of the colour from the leachate. However, when these three AOPs were evaluated, it was shown that O_3/UV had a greater oxidation ability for enhancing biodegradability and colour removal than the other two. The procedure can obtain about 85% of a smaller molecular mass chemical with fewer than 1000 Da, which is higher than ozonation alone [127].

This increase in removal effectiveness due to the combination of two oxidants in photochemical oxidation agrees with findings obtained by Wenzel et al. [140], who found that a combination of UV/H_2O_2/O_3 removes roughly 10–20% more TOC than UV/H_2O_2. However, if a greater dose of O_3 is used in the process, a combination of UV/O_3 can achieve approximately identical TOC removal to UV/H_2O_2/O_3, making it a more cost-effective approach because it does not require the addition of hydrogen peroxide. Wenzel et al. [140] also agreed that using UV/O_3 as a leachate treatment resulted in a 100% phenol and hydrocarbon degradation ratio, 23–96% for biphenyls, and 74% for dioxins and furans, with biphenyl degradation fluctuating, indicating that it is an oxidation-resistant compound. These substances must be removed since they are known to be extremely detrimental to the environment. The development of halogenated by-products can result in a rise in AOX value in some situations. The removal efficiency of low TOC concentrations can be enhanced by increasing the radiation power.

Even though a mixture of ozone and other oxidants can enhance the proportion of large molecule chemicals that are broken down into lower molecular components, it cannot totally oxidize substances like humic acids, proteins, and carbohydrates. However, because the chemicals are partially degraded, biological therapy can reduce them even further. The ability of the procedure to reduce leachate toxicity varies depending on the type of microorganism studied, whether bacteria or algae [139]. Further biological treatment has demonstrated positive results in lowering the increase in toxicity and methanogenic value following oxidation. When using a heterogeneous catalyst with ozonation in the AOP process, Pt catalyst does not yield higher COD removal than ozonation alone, and only cobalt-based catalysts gave a modest increase in COD removal. It has been revealed that UV/H_2O_2 consumes the most energy when compared to O_3 and O_3/catalyst. Photochemical oxidations, like photocatalysts, have issues with irradiation/UV penetration for brightly coloured leachate, as well as the possibility of carcinogenic intermediate by-products generated during the treatment. After the oxidation process, leftover oxidants and reagents must also be removed from the leachate. Changing the type of system employed from a common loop system to a thin-film system can solve the problem of coloured inhabitation.

8.8.3.4 Electrochemical Oxidation

Electrodes made up of oxidant/catalyst materials and chemical additives are used to treat electrochemical oxidation. The charges on the electrodes would increase the formation of free radicals and have a direct oxidation reaction with the pollutants during treatment. The process is influenced by the type of electrode used, the current density delivered, the chemical concentration added, and the most obvious factor in oxidation, the pH value. Increasing the current operating density and the concentration of the added chemical is thought to improve elimination efficiency.

This method was investigated to see if it could improve the traditional oxidation process. Chiang et al. [141] looked into the electrochemical treatment of leachate with various electrodes, current densities, and the effect of chloride concentration on the treatment. It was discovered that the production of chloride/hypochlorite, which has an indirect oxidation reaction with the pollutants and also acts as the primary removal mechanism in the process, alters the removal effectiveness. There was competition for COD and ammoniacal nitrogen removal in the treatment, with ammoniacal nitrogen being more dominant and having a higher removal efficiency. The presence of anion in the leachate affects the elimination of COD and ammoniacal nitrogen. A high concentration of sulphate (oxygen-containing anion) reduces the effectiveness of the process by preventing oxygen from interacting with the electrode surface. Complete removal of ammoniacal nitrogen and 92% elimination of COD can be achieved after 240 min of electrolysis at 15 A/dm^2 and a chloride concentration of 7500 mg/L. COD removal efficiency increased only after nearly all ammoniacal nitrogen was removed because COD and ammoniacal nitrogen removal are competitive.

Hamid et al. [10, 142–144] investigate a number of electrocoagulation techniques on saline landfill leachate from the Pulau Burung Landfill Site (PBLS) on Pulau Pinang, Malaysia. They [142] looked into the impact of electrocoagulation operational conditions such as current density (60–780 A/m^2), treatment time (5–60 min), and pH (5–10) on removing colour that was present in high concentrations. To improve the performance of the electrocoagulation reactor, a laboratory-scale batch reactor was built with an aluminium electrode (Fig. 8.26) in a parallel-monopolar arrangement directly coupled to the DC power source (60 V/5 A). Colour and salinity leachate electrolytes have initial values of 8427 Pt-Co and 15.13 ppt. The complete colour removal achieved was up to 71% at a current density of 540 A/m^2, a treatment time of 60 min, and an optimal pH of 8. The research demonstrates that using electrocoagulation to remove saline brightly coloured leachate without the need for an accessory electrolyte is a viable approach. Hamid et al. [143] investigated the behaviour of a unique zeolite enhanced on the electrocoagulation process (ZAEP) with an aluminium electrode (Fig. 8.26) to eliminate high-strength concentration ammonia from the same location in the same year. The capabilities of the treatment process were optimized using a response surfaces methodology (RSM) through central composite designs (CCD). Significant variables such as zeolite dosage, current density, electrolysis time, and initial pH, as well as the % removal of ammonia, were evaluated using Design-Expert software (version 11.0.3). The greatest reduction of ammonia was up to 71%, indicating that the following working parameters for the treatment process were optimal: zeolite dose of 105 g/L, the current density of 600 A/m^2, electrolysis duration of 60 min, and pH of 8.20. With a high R2 of 0.9871, the regression model revealed a significant link between the anticipated values and the actual experimental data. Further colour research [144]

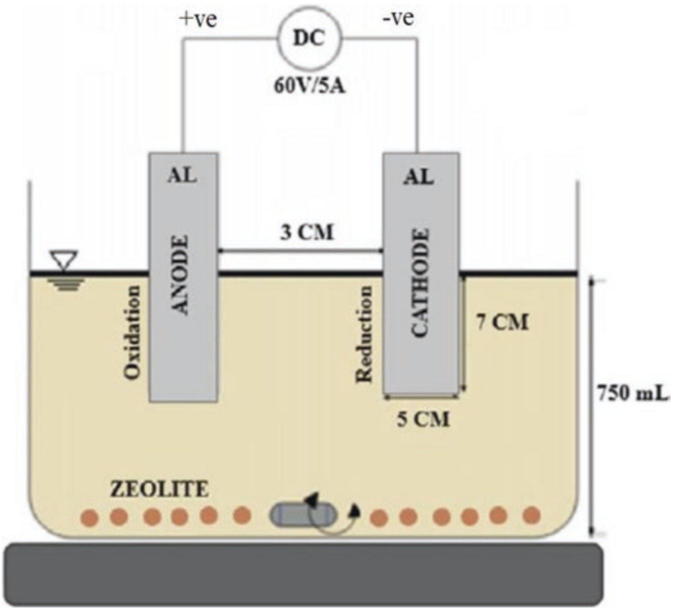


Fig. 8.26 Setting up an experiment for clinoptilolite-augmented electrocoagulation

discovered that the best-operating settings were 146 g/L zeolite dose, 600 A/m^2 current density, 60 min treatment time, 200 rpm stirring speed, 35 min settling time, and pH 9. This disease resulted in a colour loss of up to 88%. The whole operational cost was anticipated to be 26.22 \$/m^3. In all posttreatment operations, the biodegradability of the leachate had improved from 0.05 to 0.27. The hybrid technique was found to be effective in removing concentrated ammonia and colour from natural saline landfill leachate.

Hamid et al. [10] looked into a single hybrid treatment that combined a continuous clinoptilolite augmented electrocoagulation approach with a sequencing batch reactor (SBR) process to remove highly concentrated ammoniacal nitrogen (NH_3-N) and colour from PBLS (Fig. 8.27). To begin, the effects of various clinoptilolite dosages (13–187 g/L), reaction periods (5–70 min), and settling times (5–60 min) on the pollutants' removal effectiveness were explored. Adsorption kinetics were discovered to correlate to a pseudo-second-order model (R^2 close to 1). The regeneration of wasted clinoptilolite was then studied using a variety of solvents (NaCl, NaOH, HCl), solvent concentrations (0.1–1.0M), contact times (5-70 min), and reuse numbers (1–5 runs). The best removal rates for NH3-N and colour were 83% and 95%, respectively, and the best removal rates were maintained for 300 min of continuous operations with a total treatment effluent volume of over 3750 mL. With 147 g/L clinoptilolites, 60 min of reaction, 35 min of settling, NaCl as the regeneration solvent, 0.5M solvent concentration, 25 min of contact, and four reuse cycles, the best removal rates were achieved. The overall operating cost of the proposed method for removing NH_3-N and colour, according to cost estimates, is US \$8.71/

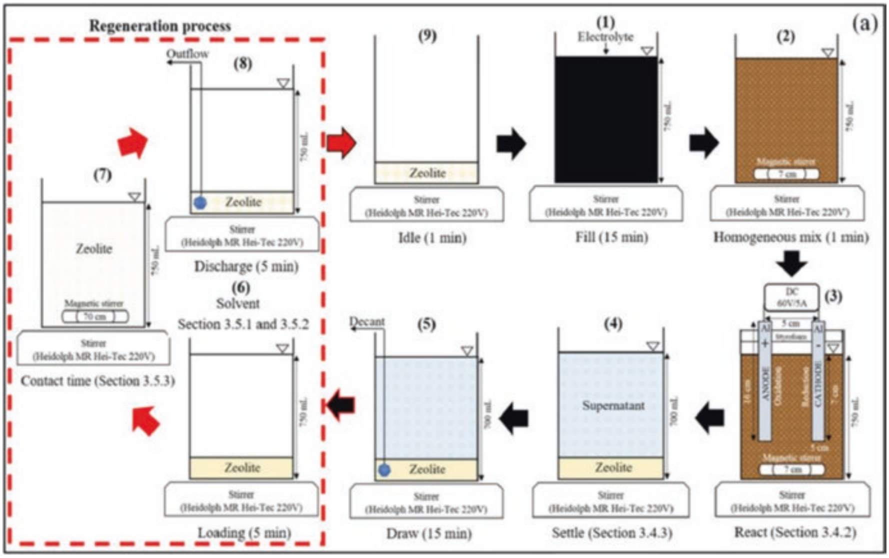


Fig. 8.27 Experimental set-up of the continuous hybrid treatment process (Clinoptilolite + EC method with SBR)

m^3/cycle. As a result, combining physical, chemical, and biological approaches into a single process to remove concentrated NH_3-N and colour from landfill leachate while maintaining sufficient salinity could be a viable option.

8.8.3.5 Fenton Oxidation

The Fenton oxidation procedure, a chemical oxidation therapy, had been the subject of an investigation by various researchers for the treatment of leachate. The Fenton reagent is made up of a ferrous (Fe^{2+}) solution as a catalyst and hydrogen peroxide (H_2O_2) as an oxidant. When ferrous ion combines with hydrogen peroxide in the Fenton process, catalytic breakdown produces hydroxyl radical (OH). The reaction between the ferrous ion and hydrogen peroxide can be simplified as follows: adding H_2O_2 to Fe^{2+} salts causes Fenton's reagent to produce OH radicals [51].

$$H_2O_2 + Fe^{2+} + \rightarrow Fe^{3+} + OH^- + OH$$

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + \cdot OH$$

The toxic and recalcitrant compounds can be removed significantly by the Fenton reaction, initiated by H_2O_2 and Fe^{2+}, which eventually improve leachate biodegradability by increasing the BOD_5/COD ratio up to 0.5 [2]. Fenton's reagent has been shown to be capable of destroying poisonous substances in wastewaters such as phenols and herbicides. This is a very common method of generating hydroxyl radicals that do not require any special reactants or equipment. According to some reports, COD removal efficiencies by Fenton processes vary from 45% to 85%, with a decolourization efficiency as high as 90%, with a very nominal ammonia reduction [18]. Optimum pH values have been identified from 2.0% to 4.5% for landfill leachate treatment by electro-Fenton, photo-Fenton, and conventional treatment methods. Although COD removal increases at a higher temperature, it causes inefficient H_2O_2 disintegration, which eventually reduces the COD removal.

As such, Fenton's reagent (H_2O_2 and Fe^{2+}) is one of the most potential AOP methods for organic pollutant oxidation. Fenton's mixture is effectively applicable (individually or in conjunction with other treatments) as a chemical process for a wide variety of leachate and wastewater treatment. It is a mechanism that works by producing highly sensitive oxidizing free radicals, especially hydroxyl (OH^-) radicals, which contains a higher oxidation potential in comparison with ozone. Ferrous ion concentration, pH, temperature, treatment time, and hydrogen peroxide are the influencing factor of this procedure. Implementation of Fenton's reagent with chemical oxidation is recognized as a feasible alternative to oxidative degradation of organic compounds, ensuring up to 90% COD removal. Nevertheless, a metallic portion in Fenton's residue might be responsible for significant environmental pollution [4].

In general, the Fenton oxidation procedure may remove around 60% of COD while also increasing the leachate's biodegradability value [145]. Using the Fenton procedure, Bae et al. [146] reduced COD by around 63%, while Lopez et al. [145] increased the biodegradability of the treated leachate from 0.2 to 0.5. Contaminants were removed not only through oxidation but also during the coagulation process after treatment with Fenton reagents. Fenton reagents' COD removal efficiency was also higher than the COD removal efficiency of the oxidation process alone. According to Lau et al. [147], H_2O_2 and Fe^{2+} had an effect on the coagulation of colloidal organic wastes, which contributed more to COD removal than the oxidation process itself. The presence of ferrous ions in Fenton reagents caused coagulation because they reacted with the pollutants to form ferric hydrosol complexes. Because the oxidation process is hampered by high ferrous ions, increasing the ferrous ion dosage to 500 mg/L will improve COD elimination through coagulation [145]. Because the fraction of non-oxidized compounds in the leachate will gradually grow during treatment, overdosing with H_2O_2 will not boost the efficiency of the oxidation process as it did with ferrous ions.

As a result, the ideal Fe^{2+}/H_2O_2 ratio dose must be determined in order to achieve optimal removal for both the coagulation and oxidation processes in the Fenton treatment. The ideal ratio dosage for efficient oxidation reaction in the treatment was usually a lower dose of Fe^{2+} than H_2O_2. According to Lopez et al. [145], the ideal H_2O_2:Fe^{2+} ratio (by mass) should be around 12. However, depending on the character and matrix of the treated leachate, the appropriate dosage ratio varies for various wastes. Overdosage of Fe^{2+} and H_2O_2 over the ideal ratio will not result in a greater oxidation process removal efficiency because these ions will generate a scavenging effect with the free hydroxyl radical [145, 147], as shown in the following reaction:

$$OH + Fe^{2+} \rightarrow OH - + Fe^{3+} \left(\text{for overdosage of } Fe^{2+}\right)$$

$$\cdot OH + H_2O_2 \rightarrow HO_2^- + H_2O\left(\text{for overdosage of } H_2O_2\right)$$

Various studies have compared the two processes because Fenton oxidation demonstrates pollutant elimination via coagulation. For removing lower molecular weight (MW) organics, the Fenton oxidation procedure has been found to be more effective than using a coagulant like $FeCl_3$. The Fenton method has a higher removal efficiency for both organics with a molecular weight (MW) greater than 500 MW when compared to the ability of a coagulant to remove organics. The Fenton method can remove 72–89% of organics with a molecular weight (MW) greater than 500 and 42% of organics with an MW less than 500, whereas coagulation only removes 59–73% and only 18% of the same organic materials, respectively [148]. Due to the high coagulation removal efficiency of Fenton reagents, the Fenton oxidation process has also been labelled as an accelerated coagulation process.

Because it does not require electrical energy, which is required in ozonation and other sophisticated oxidation processes, the Fenton oxidation method is the most technologically simple and much cheaper than other oxidation processes. When Fenton oxidation is used as a pretreatment, especially before biological treatment, the remaining ferric ions must be removed either by precipitation with $Ca\ (OH)_2$ or coagulation with polyelectrolyte, which results in sludge formation. Lower pH levels are also required for a successful Fenton oxidation process, as low pH favours the formation of free hydroxyl radicals. This is owing to the high concentration of bicarbonate in an alkaline zone, which will react with the hydroxyl radical. At pH ranges of 2.5–4, with a greater concentration of H_2O_2 for the ideal ratio, the oxidation process is the dominant removal mechanism in the Fenton treatment. Meanwhile, at pH 4–6, with ferrous ion concentrations larger than those of H_2O_2, the coagulation removal mechanism is much more dominating. At pH 6 (300 mg/L Fe^{2+} and 200 mg/L H_2O_2), Lau et al. [147] achieved 70% COD removal with only 14% COD removal owing to the oxidation process, but Kang and Hwang [149] reported 45% COD removal due to the oxidation process alone at pH 2.5–4.

With the help of a photograph Fenton, as one of the advanced oxidation processes (AOP), was also investigated in order to improve the process's removal efficiency. Irradiation by the light source utilized in the procedure generates the hydroxyl radical in addition to the decomposition of hydrogen peroxide alone [138]:

$$H_2O + Fe^{3+} + hv \rightarrow Fe^{2+} + H^+ + \cdot OH$$

After 6 h of irradiation with 1.9×10^{-1} mol/L H_2O_2 and 1.51×10^{-3} mol/L $FeSO_4 \cdot 7H_2O$, landfill leachate treated with this technique had a high removal capacity, with about 83% TOC removal [138]. Kim et al. [150] also reported that employing 1.0×10^{-3} mol/L Fe^{2+} and a molar COD:H_2O_2 ratio of 1:1 at pH 3, they were able to remove nearly 70% of COD. The process' oxidation rate was six times faster than it would have been without the radiation. When the irradiation rate is doubled, the oxidation rate can be enhanced by up to double [150]. Because irradiation may renew the consumed ferrous ions in the process, this approach was discovered to be able to reduce the quantity of ferrous salts utilized.

Photo Fenton reactions, unlike other photo-assisted oxidation methods, can be used with visible light irradiation because the Fe^{3+} complexes have broad absorption bands. Irradiation with short-wave UV radiation (254 nm) is preferred for the usage of oxidants such as H_2O_2 alone because it has minimal absorption in the near UV area. In comparison to the lengthier oxidation period required by the UV/TiO_2 and UV/H_2O_2 processes (24 h), the photo Fenton method may remove pollutants in a fraction of the time (30 min) but with lower removal effectiveness [138].

Combining the Fenton oxidation process with an electrochemical treatment called electro Fenton is another way to improve the process. Cast iron electrolytes (anodic and cathode) are used in the process, and H_2O_2 is supplied directly to the leachate. A certain amount of iron will be continually dissolved and interacted with H_2O_2 to oxidize the contaminants during the treatment. Lin and Chang [151] claim that the technique has a synergistic effect on the removal of pollutants. The electrochemical technique alone could only remove 26.7% of COD, but when 750 mg/L H_2O_2 was added to the treatment, the removal effectiveness was enhanced by a factor of 2.5 (67.3%). The ability of this method to remove contaminants is also influenced by the pH of the leachate and the amount of H_2O_2 employed. The electro Fenton process requires a low pH of around 4 to achieve high removal efficiency; however, the dose of H_2O_2 impacts not only removal effectiveness but also oxidation rate. A higher H_2O_2 concentration will require a longer oxidation period but will improve the process' removal efficiency. Even though these two process innovations (photo Fenton and electro Fenton) have been shown to improve removal efficiency and minimize oxidation time, more costs are required since UV light and electrodes require electrical and power usage.

8.8.3.6 Performances of Advanced Oxidation Processes (AOP) and Oxidants in Leachate Treatment

In water and wastewater treatment systems, the terms AOP and oxidants are interchangeable. Both use a set of chemical treatment procedures called oxidation to remove organic (and occasionally inorganic) materials from water and wastewater. The main distinction is that AOP refers to an oxidation process involving hydroxyl radicals (OH) and ozone (O_3), hydrogen peroxide (H_2O_2), and/or ultraviolet (UV) light. Tables 8.12 and 8.13 summarize the performance of leachate treatment processes (primarily AOPs) and their efficiencies over the last few years, based on Aziz and Ramli's [152] research.

Table 8.12 Summary of the efficacy of various landfill leachate treatment processes [152]

Process	Initial concentration	Removal (%)		
		COD	Colour	NH_3-N
Electro-coagulation	COD: 12,860 (mg/L), NH_3-N: 2240 (mg/L), pH: 8.2	56	–	–
Electro-Fenton	COD: 2350 (mg/L), NH_3-N: 310 (mg/L), colour: 1143(Abs.), pH: 8.36	72	90	28
Fenton	COD: 34,920 (mg/L), pH: 5.1	50.79	–	–
Fenton	COD: 2340 (mg/L), NH_3-N: 1055 (mg/L), pH: 8.26	63	76	–
Coagulation/flocculation+ PAC	COD: 2817 (mg/L), NH_3-N: 2000 (mg/L), pH: 8.6	70 - 86	–	–
Photo-Fenton	COD: 3823 (mg/L), NH_3-N: 2016 (mg/L), pH: 7.94	86	100	–
Photo-Fenton	COD: 1320 (mg/L), NH_3-N: 260 (mg/L), pH: 8.36	80	–	–
Photo-Fenton	COD: 1960–2880 (mg/L), colour: 2160–2560 (Pt-Co.), NH_3-N: 730–980 (mg/L), pH: 8.4–8.7	70	80	80
Persulphate ($Na_2S_2O_8$)	COD: 1270 (mg/L), NH_3-N: 2000 (mg/L), pH: 8.3	91	–	100
Persulphate ($Na_2S_2O_8$)	COD: 2451(mg/L), pH: 7.9	39	79	–
Persulphate/AC ($K_2S_2O_8$/AC)	COD: 275(mg/L)	77.8	–	–
Ozonation	COD: 560 (mg/L), pH: 10	40		
Ozonation	COD: 5230 (mg/L)	27	87	–
Ozonation	COD: 3945 (mg/L), NH_3-N: 800 (mg/L), pH: 4.5	48	–	–
Ozonation	COD: 1090 (mg/L), colour: 1130 (TCU), NH_3-N: 455 (mg/L), pH: 8.5	73	90	67
Ozonation	COD: 2422 – 3954 (mg/L), NH_3-N: 750–800 (mg/L), pH: 8–8.5	40	–	–
Ozonation	COD: 7800 - 8200 (mg/L), NH_3-N: 1690–1810 (mg/L), pH: 8.4–8.6	49	–	–
Ozone + hydrogen peroxide (O_3/H_2O_2)	COD: 1740 (mg/L)	93		
Ozone + hydrogen peroxide (O_3/H_2O_2)	COD: 5678 (mg/L), pH: 8.7	60–90		
Ozone + ultraviolet radiation (O_3/UV)	COD: 7800–8200 (mg/L), pH: 8.4–8.6	78		
Adsorption via composite adsorbent (activated carbon, zeolite, limestone, and rice husk ash)	COD: 1478–3540 (mg/L), Colour: 3773–5100 (Pt-Co.), NH_3-N: 1010–2740 (mg/L), pH: 8.1–8.7	65	98	70

(continued)

Table 8.12 (continued)

Process	Initial concentration	Removal (%)		
		COD	Colour	NH_3-N
Adsorption (carbon-zeolite composite adsorbent)	COD: 2033 (mg/L), NH_3-N: 1920 (mg/L),	57.5		37
Adsorption (durian peel-based activated carbon)	COD: 3100 (mg/L), NH_3-N: 3286 (mg/L),	41.9	39.9	
Powdered activated carbon-sequential bach reactor (SBR)	COD: 1396 (mg/L), colour: 3262 (Pt-Co.), NH_3-N: 579 (mg/L), pH: 8	27.3	65.4	89.9
Powdered ZELIAC-sequential bach reactor (SBR)	COD: 1301 (mg/L), colour: 1690 (Pt-Co.), NH_3-N: 532 (mg/L), pH: 8.25	72.84	84.1	99.0

Source: Hamidi and Amr [33]

Table 8.13 Summary of the treatment efficiencies of different semi-aerobic landfill leachate treatment processes [152]

Process	Initial concentration	Removal (%)		
		COD	Colour	NH_3-N
Coagulation/flocculation	COD: 1925 (mg/L), NH_3-N: 1184 (mg/L), colour: 3869 (Pt-Co.), pH: 8.4	43.1	94	–
Anionic resin	COD: 2380–2850 (mg/L), NH_3-N: 1820–2200 (mg/L), pH: 8.3–9.10	70.3	91.5	–
Flotation + coagulation ($FeCl_3$)	COD: 2610 (mg/L), colour: 4000 (Pt-Co.)	75	93	41
Fenton	COD: 2950 (mg/L), colour: 3850 (Pt-Co.), pH: 8.5	58	78	–
Electro-Fenton	COD: 2950 (mg/L), colour: 3850 (Pt-Co.), pH: 8.5	94.07	95.83	–
PAC-SBR	COD: 1655 (mg/L), colour: 3672 (Pt-Co.), NH_3-N: 600 (mg/L), pH: 7.87	64	71	81
Ion exchange process	COD: 2667 (mg/L), colour: 4059 (Pt-Co.), NH_3-N: 1760 (mg/L), pH: 8.2	87.9	96.8	93.8
Flotation + coagulation alum ($Al_2(SO^4)_3$)	COD: 2610 (mg/L), colour: 4000 (Pt-Co.), NH_3-N: 1975 (mg/L), pH: 8.13	79	70	-
$O_3/H_2O_2/Fe$	COD: 2180 (mg/L), colour: 4100 (TCU), NH_3-N: 1065 (mg/L), pH: 8.5	65	98	22
$O_3/H_2O_2/Fe$	COD: 1780 (mg/L), colour: 3450 (TCU), NH_3-N: 780 (mg/L), pH: 8.5	78	98	22
$O_3/S_2O_8^{2-}$	COD: 2480 (mg/L), colour: 3450 (TCU), NH_3-N: 810 (mg/L), pH: 8.5	72	96	55
$O_3/S_2O_8^{2}$	COD: 2025 (mg/L), colour: 3550 (TCU), NH_3-N: 810 (mg/L), pH: 8.5	72	96	76

8.8.4 Coagulation-Flocculation

8.8.4.1 Introduction and Mechanism

A coagulant is a chemical that is added to a liquid to destabilize particles and promote the aggregation of colloids and the production of flocs [153]. The coagulants are propelled by colloidal particles that neutralize the charges [154]. Coagulants come in a variety of forms and could be used to treat water and wastewater, particularly leachate. Inorganic materials (such as aluminium and ferric salts) and natural materials can be used as coagulants [155]. Flocculants are substances that aid in the coagulation process by speeding up the purification and improving the performance of the sludge solution. A flocculant, also known as a coagulant aid, is a substance used to facilitate the flocculation process in the treatment of water and wastewater [156]. The three types of flocculants accessible are chemical flocculants, natural flocculants, and grafted flocculants [156]. Anionic and non-ionic polymeric flocculants are commonly used to enhance the aggregation and agglomeration of slow-settling micro-flocs generated by coagulants, resulting in larger and denser flocs that are easier to remove during the sedimentation, floating, and filtering stages, according to Lee et al. [157].

Flocculants can reduce the use of coagulants and increase the workability and capacity of wastewater treatment by enhancing the density and strength of the floc produced [156]. Water and wastewater are treated with coagulation-flocculation, a basic physical-chemical process. It is commonly used to treat leachate and is used as a pretreatment before biological treatment to remove heavy metals and non-biodegradable organic compounds from landfill leachate [158]; to remove turbidity, colour, contaminants, and microorganisms [159]; and to remove colloidal and suspended solids, natural organic matter, odours, and metal ions [158, 160]. According to Sahu and Chaudhari [161], coagulation and flocculation processes take place in a sequence of steps aimed at overcoming the strength of stabilizing suspended particles, permitting particle collisions, and encouraging floc growth. As a result, the primary purpose of the coagulation-flocculation process is to produce a floc by adding coagulant salt to the water, which causes small particles to clump together and form a macro floc, which can then be settled and filtered directly [162, 163].

Coagulation-flocculation is primarily based on electrical characteristics, according to Yusoff et al. [164]. For example, leachate contains a number of negatively charged particles (−30 to −40 mV) that can interact with one another. As a result, obtaining positively charged coagulants that will neutralize the charge is crucial for the combination of a positive and negative charge. Coagulants such as metal salts rapidly hydrolyse in wastewater at an isoelectric point to produce cationic species, which colloidal particles with negatively charged adsorbed concurrently, reducing the surface charge and forming micro floc, according to Suopajärvi et al. [165]. The charge neutralization of negatively charged colloids by cationic hydrolysis products, followed by a combination of pollutants in an amorphous hydroxide precipitate through flocculation, is the key removal mechanism of this process [166].

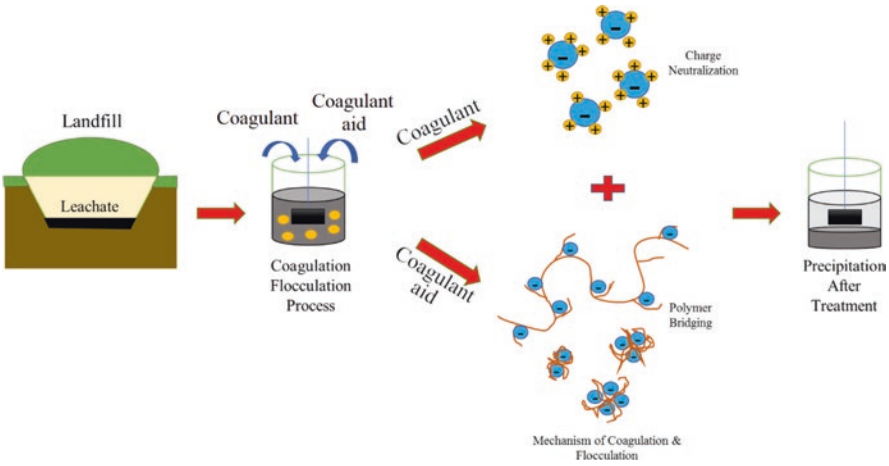


Fig. 8.28 Schematic diagram of the most common coagulation-flocculation process and the mechanisms

Chemicals known as coagulants are added to the leachate during the coagulation process, affecting the stability of colloidal particles in the sample. The colloidal particles clump together and form larger flocs that can be filtered out of the leachate in a reasonable amount of time as a result. Coagulation is the process of quickly mixing coagulants into the leachate, followed by progressive flocculation stirring to achieve the desired floc size for settlement. Coagulation and flocculation are commonly used to remove colloidal particles that take a long time to settle, but they can also be used to remove nutrients. Several studies have looked into coagulant types and doses, pH influence, leachate properties, and sludge development, all of which are critical for effective coagulation-flocculation leachate treatment.

Through the addition of coagulants, impurities are removed in the shape of colloidal or suspension by coagulation and flocculation (Fig. 8.28). Aluminium or iron salts are typically applied as coagulants at controlled pH to form floc, which is a dense precipitate containing colloidal particles that can be separated using standard liquid-solid segregation techniques. The applied coagulants are extremely important since they influence the coagulation process [167]. Flocculation promotes floc development by light blending, which aids the segregation process. Polyelectrolyte compounds might be applied to increase coagulation by encouraging the formation of larger and fast-setting flocs [8].

Flocculation is a procedure used to improve the extraction of non-settle able colloidal solids (such as humic acids, surfactants, fatty acids, and heavy metals). Coagulation-flocculation, in particular, allows for the efficient removal of colour, SS, and turbidity with removal rates of 92% turbidity, 90% SS, and 80% COD. This process might be used to avoid fouling as pretreatment before MBR [168]. Indeed, it is often used before reverse osmosis or biological treatment or after leachate final

Table 8.14 Major coagulants applied for leachate treatment

Major coagulants used in leachate treatment		
Natural polymers	Polymeric metallic salts	Metallic salts
1. *Hibiscus rosa-sinensis* 2. Natural starch: (a) sago trunk, (b) jackfruit seed, (c) cassava seed, (d) palm oil trunk 3. Moringa seed 4. Chitosan and pine bark 5. Tobacco leaf 6. Psyllium husk 7. Lateritic soil 8. Glutinous rice flour 9. *Tamarindus indica* 10. Tanin, etc. *Synthetic* 1. Polyalkylene 2. Polyamines 3. Epichlorohydrin 4. Polyacryl amides 5. Poly ethyl amines	1. Polyaluminium chloride 2. Polyaluminium sulphate chloride 3. Polyferric sulphate 4. Poly iron chloride 5. Aluminium chlorohydrate	1. Aluminium sulphate 2. Aluminium chloride 3. Ferric chloride. 4. Ferric sulphate 5. Sodium aluminates 6. Ferrous sulphate

cleaning functions. Ferric chloride ($FeCl_3$), ferrous sulphate ($FeSO_4$), and aluminium sulphate ($AlSO_4$) are the major coagulants, among others, as listed in Table 8.14.

8.8.4.2 Type of Coagulants

Coagulants are compounds that are either naturally occurring (such as starch or iron and aluminium salts) or synthesised and used in leachate and wastewater treatment (cationic, anionic, and nonionic polymers). Coagulants such as aluminium sulphate (alum), ferrous sulphate, ferric chloride, and ferric chlorosulphate are commonly used for coagulation-flocculation treatment [10, 28, 40, 59, 95, 96, 100, 103, 105, 107, 109]. For many years, lime has been the traditional coagulant for leachate treatment [10]. For landfill leachate treatment, 1–15 g/L of lime is typically required to achieve good removal of heavy metals (up to 90%) and removal of colour, turbidity, suspended matter, and dispersed oils (70–90%) [10]. Not only is calcium hydroxide (lime) used as a coagulant, but it is also used to change the pH of leachate. When used as a coagulant at pH 12 and a dose of 7 g/L, calcium hydroxide (lime) can remove COD in the range of 30–45%. [103].

However, using lime as a coagulant has a number of drawbacks, including raising the pH and hardness of the leachate. Furthermore, a big dose of alum would produce an excessive amount of sludge. Lime is typically utilized only for pH correction rather than as coagulants in the coagulation-flocculation process for these reasons. Table 8.15 lists the pros and downsides of various coagulants.

$FeCl_3$ is efficient for leachate with lower pH values and higher density of dissolved organics (COD>5000 mg/L), while the flocculants enhance the removal

Table 8.15 Different coagulants' benefits and drawbacks [110, 169, 170]

Coagulants	Advantage	Disadvantage
Ferric chloride $FeCl_3{\cdot}6H_2O$	Wide effective pH range (4–11) Easier settlement than alum	Depend very much on the alkalinity
Ferric sulphate $Fe_2(SO_{4)3}$	Effective pH range between 4–6 and 8.8–9.2	Depend very much on the alkalinity
Ferrous sulphate $FeSO_4{\cdot}7H_2O$	Not quite sensitive to pH changes than lime Effective at high pH value	Required addition of alkalinity More effective at high pH value
Aluminium sulphate (alum) $Al_2(SO_4)_3{\cdot}18H_2O$	Easy handling, cheap, insignificant amount of sludge, effective pH range of 4–6	Limited range of effective pH Associated with Alzheimer if overdosage
Lime $Ca(OH)_2$	Effective for water containing low organic matters No metallic salts addition	Depend very much on pH. A significant amount of sludge Overdosage caused low effluent quality
Sodium aluminates $Na_2Al_2O_4$	Effective for high alkalinity wastewater, only small doses required	Usually used with alum, high cost, and not effective for soft water
Polyaluminium chloride $Al_{13}(OH)_{20}(SO_4)_2{\cdot}Cl_{15}$	Form larger flocs, faster settlement than alum	Costly

efficiencies of coagulants [171]. $FeCl_3$ (3000 mg/L) can efficiently remove 68% COD and 85% turbidity, whereas, after adding optimum flocculants, it can eliminate almost 100% turbidity and 65% COD. Sludge generation is another critical consideration for determining the appropriate coagulants or flocculants. According to Assou et al. [171], $FeCl_3$ produces 700 ml/L sludge from coagulation for 3000 mg/L dosage. Moreover, the combination of pre-polymerized coagulants with conventional chemical coagulants is a recent technique for increasing the removal efficiencies through the coagulation-flocculation process. Therefore, the coagulation process is more effective for matured leachate than young (landfill age <5 years) leachate.

Because of their multivalent properties, which powerfully charge colloidal particles and have been shown to be effective in the majority of coagulation-flocculation treatments, aluminium and iron salts are the most commonly used coagulants in the coagulation-flocculation process. It has a high degree of elimination due to its relative insolubility in the typical pH range, and it is also reasonably priced. According to the Schulze-Hardy rule, which states that the effectiveness of an ion grows as the number of charges it contains, the efficiency of a coagulant is closely linked to its charge. Table 8.16 shows the relative coagulation capability of common coagulants.

The reaction of aluminium and iron salts in the coagulation-flocculation process may be written as follows:

$$Al^{3+} + 3HCO_3^- \rightarrow Al(OH)_3 + 3CO_2$$

Table 8.16 Effectiveness of coagulants [172]

Electrolyte	The relative power of coagulation	
	Positive colloids	Negative colloids
FeCl	1	1000
$Fe_2(SO_4)_3$	30	>1000
$AlCl_3$	1	1000
$Al_2(SO_4)_3$	30	>1000
NaCl	1	1
Na_2SO_4	30	1
Na_3PO_4	1000	1
BaCl	1	30
$MgSO_4$	30	30

$$Fe^{3+} + 3HCO_3^{-} \rightarrow Fe(OH)_3 + 3CO_2$$

In general, the removal of COD using lime, iron, and aluminium salts is low in all coagulation-flocculation experiments on leachate treatment, especially for the treatment of high-strength leachate. In terms of other metrics, Tatsi et al. [122] were able to remove about 100% of colour from partially stabilized leachate but only 93% from fresh leachate. Coagulation-flocculation treatment for semi-aerobic leachate yielded similar high colour removal, indicating that the coagulation-flocculation procedure is quite successful for colour removal. The substantial differences in characteristics between fresh, intermediate (semi-aerobic), and old leachates account for the variance in removal effectiveness of the method for these leachates. Fresh leachate has a higher quantity of dissolved organic matter (DOM) and humic material than older leachate. The hydrolysis, precipitation, and adsorption processes of ferric cations have been shown to be affected by the presence of humic compounds [122]. As a result, the unique interaction between humic substances, the surface of flocculates, and dissolved ferric species has a significant impact on the effectiveness of the coagulation-flocculation process. Furthermore, the majority of organics in high-strength leachates are low-molecular-weight volatile fatty acids that cannot be precipitated. Coagulation-flocculation is also substantially more successful in removing organic debris with a higher molecular weight [92, 115]. According to Yoon et al. [148], coagulation eliminates 59-78% of organics with a molecular weight (MW) of more than 500, but only 18% of organics with an MW less than 500.

The biodegradability value of leachate after the coagulation process remains low in terms of the BOD_5/COD ratio, posing a problem for biological treatment of the effluent. Ehrig [91] discovered a link between BOD5/COD ratio and flocculation effect, whereas COD and Absorbable Organic Halogens (AOX) removal was only 40-60% with methanogenic phase leachate (with BOD/COD ratio=0.1). Toxicity is an important parameter to consider in addition to biodegradability, especially if biological therapies are required. The effect of the coagulation-flocculation process on leachate toxicity is difficult to determine because leftover metal ions from the coagulants may have an effect on the investigated species. The use of coagulation-flocculation therapy to remove nitrogen is also ineffective [28, 91, 122]. This is in line with Chen's findings [36], which showed that chemical coagulation was less effective at removing nitrogen, with removal rates of only 58.7% and 58.6% for $FeCl_3$ and poly aluminium chlorides (PAC), respectively. Colloidal matter and albuminoid-type nitrogen (nitrogen in the form of a protein) are the main sources of nitrogen removal [122]. Coagulation-flocculation treatment, on the other hand, can remove phosphorus from leachate almost completely.

Electrocoagulation has been introduced and applied to the treatment of leachate, obviating the need to remove leftover coagulants following treatment. Fe and Al electrodes are used as anodes in the treatment. Using a pair of electrodes (Fe-Cu and Al-Cu), electrocoagulation can remove 30–50% of COD, with Fe-Cu electrodes being more effective [173]. The electrodes' different removal efficiency could be due to the formation of scum made of abundant Al3+ that covers them and reduces their active surface. Scum formation is proportional to the operating current for both electrodes, according to Tsai et al. [173], and it also inhibits the coagulation process. The procedure is favoured by a higher pH value, and it can remove organic molecules of both bigger and smaller molecular weights (MW). However, coagulation was the sole way to remove larger MW compounds, while smaller MW compounds were oxidized to VOC or CO_2.

8.8.4.3 Factor Influencing Coagulation-Flocculation (C-F)

In the coagulation-flocculation process, there are various aspects to consider. These factors include coagulant and flocculant type and dose, pH/Alkalinity, contact duration (retention time, mixing speed and time), and temperature [158, 174–179]. Among the aforementioned parameters, pH and coagulant dosage have the greatest impact on treatment effectiveness.

8.8.4.3.1 Effect of pH

The term pH refers to the concentration of hydrogen ions in a solution and is always used to describe a solution's acidity and alkalinity. The pH of a coagulant's efficacy is frequently influenced by it. It influences particle surface charge, natural organic matter (NOM), and coagulant solubility. The acidic metal coagulants consume the alkalinity, lowering the pH. pH must be maintained because coagulation occurs within a specific range for each coagulant [180]. Controlling pH and alkalinity, according to Imran et al. [181], is also critical for maintaining performance. The pH range used during the coagulation process could be the most crucial component in ensuring effective coagulation. The majority of coagulation issues are caused by inappropriate pH values, despite the fact that each coagulant has its own ideal pH. Furthermore, alkalinity is linked to pH and refers to the capacity of water as a buffer and its ability to neutralize acidic liquids. High alkalinity waters have a high pH, and acidity waters have a low pH.

8.8.4.3.2 Effect of Dosage

Coagulant dose is optimal for maximal contaminant clearance. At smaller doses, charge neutralization is possible. When the critical coagulant concentration is exceeded, restabilization occurs, resulting in greater residual in the treated water. The optimal coagulant dosage is proportional to the colloid concentration. When colloid concentration is low, interparticle interaction is reduced, resulting in a slower coagulation rate [180]. When using a different coagulant with a different sample of water or wastewater, the dosage must be adjusted accordingly. The dose of a coagulant is also affected by particle size. This means that the higher the surface area per unit of solid weight, the smaller the particle size. As a result, the higher dose required to coagulate small particles is not uncommon. Because a minor drop in particle size can increase the coagulant dosage, this rise is not linear [182].

The optimum dosage is the maximum or best amount of coagulant used in an experiment during coagulation-flocculation. The ideal dose will lower the system's efficiency as the dose is increased. At low doses or below the optimum dose, the amount of coagulant is insufficient to alter particle stability, whereas excess doses leave the leftover solution with an excess coagulant for attachment, and the particles become restabilized [161]. As a result, determining the proper dosage is one of the most crucial things to consider in order to achieve optimum coagulation and flocculation results.

8.8.4.3.3 Effect of Contact Time

Rapid mixing is required for uniform coagulant dispersion, adsorption, charge neutralization, and destabilization through the bridging mechanism, but slow mixing is required for sweep coagulation [180]. Because of the faster chemical reaction, the mixing speed should be faster when using a lower coagulant dose. According to Lapsongpon et al. [183], contact time has an impact on the percentage of organic matter removed and its characteristics.

8.8.4.3.4 Effect of Temperature

Fluid and particle motion, interparticle interaction, metal coagulant hydrolysis, adsorption, and precipitation rates are all affected by temperature [184]. When the temperature is higher, the rate of coagulation improves. When the temperature dropped from 23 °C to 15 °C, Ozbelge et al. [185] found that coagulation with ferric chloride ($FeCl_3$) resulted in poor floc settling. Chemical reaction rates deteriorate with decreasing temperature in general [180]. Furthermore, in murky water and at a lower temperature, there is less Brownian and Van der Waals movement, which accelerates the rate of chemical reactions [186].

8.8.4.4 Residual Metal and Sludge

Other disadvantages of the coagulation-flocculation technique should be considered. The use of aluminium and iron salts for coagulation-flocculation will increase the residual Fe^{3+} or Al^{3+} in the sludge. This has an impact on the treatment's economic feasibility because significant treatment is required to remove any remaining Fe^{3+} or Al^{3+} in the sludge, which must be managed and disposed of carefully. The amount and quality of sludge depend a lot on the coagulants used, the operating parameters of the treatment system, and the leachate characteristic. Sludge is made up of organic debris, solids, and chemical compounds formed by a chemical used in the treatment. A few studies have been conducted to reduce the cost of sludge disposal by recovering material, particularly alum used in the treatment, and modifying sludge reuse if recovery is not possible. The sludge recovery procedure has been shown to reduce sludge by up to 80% and lower operational costs [122], even if the purity of the recovered alum is low and no longer acceptable for the treatment of potable water. Meanwhile, sludge may be reused for other purposes depending on the content of the sludge or after appropriate sludge treatment (for example, agriculture). Table 8.17 shows the results of the survey for leachate coagulation-flocculation investigations.

Example:

Calculate the daily amount of ferric chloride needed to coagulate a leachate flow of 600 m^3/day. When 1 l of water is dosed with 6 mL of 30 g/L ferric chloride solution, optimal coagulation occurs, according to the jar test.

Solution:

$$\begin{aligned}\text{Concentration of coagulant} &= (6\,\text{ml}/1000\,\text{ml}) \times (30 \times 1000\,\text{mg}/\text{L}) \\ &= 180\,\text{mg}/\text{L}\end{aligned}$$

Amount of daily ferric chloride

$$\begin{aligned}&= (\text{coagulant's concentration}) \times (\text{flow}) \\ &= (180\,\text{mg}/\text{L}) \times (600\,\text{m}^3/\text{day}) \\ &= 108\,\text{kg}/\text{day} \\ &= 0.108\,\text{ton}/\text{day}\end{aligned}$$

Table 8.17 Application of several coagulant and flocculants in landfill leachate treatment in Malaysia

Coagulant	Flocculant	Site landfill	pH optimum	Dosage coagulant optimum (g/L)	Dosage flocculant optimum (g/L)	Percentage removal (%)					Remarks	References
						SS	Colour	COD	NH_3-N	Turbidity		
PAC	Jackfruit seed starch	Leachate Kuala Sepetang (KSLS)	5	0.6	0.5	94.5	93.3	31.6	13.1	92.3	Addition of JSS succeeded to reduced 33.3% the usage of PAC	[187]
PAC	–	Leachate Kuala Sepetang (KSLS)	5	0.9	–	95.6	93.5	13.9	9.7	90.3	–	[187]
Titanium tetrachloride ($TiCl_4$)	–	Pulau Burung Landfill Site (PBLS)	6	0.6	–	86.7	81.4	–	58.4	–	UV_{254} = 76.5%	[188]
Zirconium (IV) chloride ($ZrCl_4$)	–	Pulau Burung Landfill Site (PBLS)	4	1.5	–	93.4	94.3	–	–	–	UV_{254} = 97%. Ammonia could not be removed by the coagulant, with only 2.2% of removal	[189]
PAC	Commercial sago starch (CSS)	Pulau Burung Landfill Site (PBLS)	6	2.0	5.0	99.0	94.7	17.2	4.9	98.8	–	[190]
PAC	Native sago trunk starch (NSTS)	Pulau Burung landfill site (PBLS))	6	2.0	6.0	99.2	94.7	35.5	2.4	98.9	–	[190]

Coagulant	Flocculant	Site landfill	pH optimum	Dosage coagulant optimum (g/L)	Dosage flocculant optimum (g/L)	Percentage removal (%)					Remarks	References
						SS	Colour	COD	NH_3-N	Turbidity		
Commercial sago starch (CSS)	–	Pulau Burung landfill site (PBLS)	4	6.0	–	29.5	15.1	28.0	10.7	–	–	[190]
Native sago trunk starch (NSTS)	–	Pulau Burung landfill site (PBLS)	4	7.0	–	27.9	13.1	1.7	8.2	–	–	[190]
Iron chloride ($FeCl_3$)	–	Matang landfill site (MLS)	6	1.5	–	97.0	95.0	62.0	8.0	–	–	[191]
Iron chloride ($FeCl_3$)	–	Matang landfill Site (MLS)	5	3.6	–	–	95.54	–	–	97.78	–	[192]
Chitosan	–	Matang Landfill Site (MLS)	4	0.06	–	–	14.67	–	–	23.52	–	[192]

Alum	*Psyllium husk*	Pulau Burung landfill site (PBLS)	6.5	10.0	0.4	81.0	82.0	63.0	–	–	–	[193]
Alum	–	Pulau Burung landfill site (PBLS)	6.5	11.0	–	96.0	90.0	64.0	–	–	–	[193]
Durian seed starch (DSS)	–	Matang landfill site (MLS)	6	4.0	–	–	34.0	–	–	28.0	–	[194]
PAC	Tobacco leaf	Alor Pongsu Landfill Site (APLS)	6	1.5	1.0	48.0	86.0	91.0	–	–	–	[195]

(continued)

Table 8.17 (continued)

PAC	*Tamarindus indica* seed (TIS)	Alor Pongsu Landfill Site (APLS)	6	2.75	2.0	99.3	97.3	67.4	–	–	–	[196]
PAC	–	Alor Pongsu Landfill Site (APLS)	6	5.0	–	99.5	97.4	73.6			–	[196]
Tamarindus indica (TIS)	–	Alor Pongsu Landfill Site (APLS)	4	5.0	–	5.9	41.9	0	–	–	Addition of TIS succeeded to reduced 55% the usage of PAC	[196]
PAC	*Dimocarpus longan* seeds (LSP)	Alor Pongsu Landfill Site (APLS)	6	2.75	2.0	99.5	98.8	69.2	–	–	–	[196]
PAC	–	Alor Pongsu Landfill Site (APLS)	6	5.0	–	99.5	98.0	67.4	–	–	–	[196]
Dimocarpus longan seeds (LSP)	–	Alor Pongsu Landfill Site (APLS)	4	2.0	–	39.4	22.2	28.3	–	–	–	[196]
PAC	–	Kulim landfill site (KLS)	7	0.5	–	98.0	100	70.0	–	92.0	–	[197]
PAC	–	Kuala Sepetang landfill site (KSLS)	6	1.0	–	94.0	95.0	70.0	–	96.0	–	[197]
Lateritic soil		Pulau Burung Landfill Site (PBLS)	2	14	–	–	81.8	65.7	41.2	–		[198]

8.8.4.5 Adverse Consequences of Chemical Coagulants on Human Health and Environment

Although inorganic metallic coagulants have been used for wastewater treatment since the eighteenth century [199], the long-term sustainability of the treatment process has been linked to neurological diseases such as Alzheimer's disease, particularly when residual aluminium penetrates the human body and accumulates in the brain [200]. In addition, typical inorganic coagulants cause increased sludge volume [201], which is difficult to treat and expensive to dispose of [63]. Even after the created sludge is disposed of, the metallic toxicity in groundwater increases [202]. Because organic synthetic polymers are not readily biodegradable and some of them produce monomers, they have been reported to cause pathological stress, false satiation, reproductive complications, blocked enzyme production, reduced growth rate, and oxidative stress [203]. Chemical coagulants are also nearly prohibitively expensive, which raises the treatment's operational costs [204]. As a result, developing environmentally friendly coagulating agents to promote clean growth mechanisms while limiting environmental and human health risks is seen as a critical issue in leachate and wastewater treatment [205].

8.8.4.6 Advantageous Concerns of Natural Coagulants for Leachate Treatment

The substitution of chemical coagulants with natural polymeric materials had already been proved to minimize the negative impact of chemical coagulants on live organisms [206]. Natural coagulants, particularly plant extracts, are always readily available and regarded as toxin-free [207]. Even though several studies have demonstrated the positive impact of using natural organic coagulants such as *Hibiscus rosa-sinensis*, Chitosan, Cassava peel, oil palm trunk starch, and others because they are renewable resources [208], accessible even in remote areas, relatively low cost, and environmentally friendly [209], they are assumed safe for both terrestrial and aquatic environments. Several species of natural coagulants with their quite effective medicinal properties and dietary rich resources exist in different regions of the world. These can be used in the coagulation-flocculation process as a sustainable and green approach to landfill leachate treatment. Many authors have reported about containing the complex carbohydrates in different natural coagulants that are stored in both its inner and outer layers. Besides their capacity to retain water, containing other complex carbohydrates such as D-galactose, L-rhamnose, L-arabinose, and galacturonic acid are also mentioned [210]. So, the processes of implementing natural coagulants, either alone or in combination, are displayed in Table 8.18 under an individual heading.

Table 8.18 Summary of the outcomes of applying natural coagulants

Sl. no.	Name of the coagulants	Opt. pH value	Optimum dosage	Removal of pollutants (%)	Reference
1	*Hibiscus rosa-sinensis*	6	4000mg/L alum + 500mg/L	Colour 61%, Fe^{3+} 100%, SS 72%, turbidity 60%, NH_3-N 28%	[211]
2	Sago trunk starch	6	2000 mg/L PAC + 6000 mg/L NSTS	Colour 94.7%, SS 99.2%, NH_3-N 2.4%, turbidity 98.9%, COD 35.5%, organic UV 69.5%, Cd 53.8%	[190]
3	Psyllium husk	7.5	7.2 g/L PAC + 0.4g/L Psy. husk	COD 64%, colour 90%, TSS 96%	[193]
4	Moringa seeds	7.89	37.5 g/L	Colour 92%, turbidity 85%, conductivity 64%, suspended & volatile solids 90%, COD 82%, and BOD_5 89.85%	[212]
5	*Abelmoschus esculentus* (Okra)	7.89	37.5 g/L	Colour 72%, turbidity 35%, suspended & volatile solids 87%, conductivity 20%, COD 78%, and BOD_5 72%	[212]
6	Lateritic soil	2.00	14 g/L	COD 65.7%, colour 81.8%, ammonia nitrogen 41.2%	[198]
7	Pine bark	7	4 g/L	Turbidity 85.2%	[206]
8	Chitosan	6	0.6 g/L, 60 mg/L	Turbidity 85.2%, colour 32%	
9	Glutinous rice flour	6	Alum 2.5 g/L+ glutinous RF 0.12 g/L	Colour 95%, suspended solids 91%	[213]
10	Jackfruit seed starch	5	PAC 600 mg/L; JSS 500 mg/L	COD 33.5%, colour 93.6%, SS 94.5%, turbidity 92.3%, NH_3-N 14.1%	[187]
11	Tapioca starch	5	0.2 g/L	SS 98%, colour 96%, COD 60%, ammonia 12%	[214]
12	Oil palm trunk starch (OPTS)	7	500 mg/L	Turbidity 38%, suspended solids 72.0%, COD 45.1%, colour 24.6%, NH_3-N 12.9%, Fe 29.3%, Mn 82.9%, Cu 95.6%, Zn 100%, and PO_4 91.4%	[164]
13	Cross-linked oil palm trunk starch (COPTS)	8.3	1000 mg/L	Turbidity 43.2%, suspended solids 25%, COD 65.1%, colour 39%, NH_3-N 5%, Fe 0%, Mn 100%, Cu 49%, Zn 79.5%, PO_4 100%	
14	*Ocimum basilicum*	7	1:1 ratio with alum	COD 64.4%, colour 77.8%	[215]
15	Tobacco leaf (TL)	6	1000 mg/L PAC +1000 mg/L TL	Colour 86%, COD 91% turbidity 21%, SS 48%, NH_3-N 54%	[195]
16	*Tamarindus indica*	6	2000 mg/L	SS 99.3%, colour 93%, COD 73.6%	[196]

8.8.5 Electrochemical Process

Electrochemical treatment methods are usually applied for stabilized leachates, which consist of an electrochemical cell composed of a cathode and an anode to function inside the leachate pollutants. Electro-flotation, electro-oxidation, and electro-coagulation/electro-flocculation are all electrochemical methods used to treat leachate. Iron or aluminium, or iron electrodes and electric current are required to be inserted into the leachate for conducting electrochemical operations. Small bubbles are formed during electro-flotation. Oxygen and hydrogen gases are gathered in anode and cathode, respectively. Sedimentation and flotation are the ways through which the precipitates could be removed. Furthermore, organic and ammoniacal-nitrogen oxidation may take place at either the anode directly via the solution's degradable components [8]. Electro-coagulation (EC) procedure uses electrodes to supply ions to a solution for the agglomeration of dissolved, suspended and emulsified pollutants. Electro-coagulation can be divided into three stages:

a. Coagulating electrode formation through electrolytic oxidation
b. Destabilization of contaminants and suspended particles to agglomerate
c. Accumulation of destabilized phases, resulting in the formation of flakes

The materials applied for electrode, reactor configuration, conductivity, and raw leachate density are all variables that can affect the electro-coagulation process. Iron is recognized as the best electrode since it is less susceptible to inhibitor phenomena, takes less electricity, and is less acidic, although aluminium shows better removal efficiencies [216]. The gap between the electrodes can also affect the efficiency with which contaminants in the leachate are extracted. Some experiments, however, contradict each other, and the influence of distance as an operating parameter is proven [4]. A large volume of energy consumption is the disadvantage of electro-coagulation, so it is vital to maintain a balance between removal efficiency and power consumption.

Electrical conductivity is significant in electro-coagulation since lower conductivity reduces current efficiency and requires a higher applied potential to avoid electrode inactivation, resulting in increased power consumption. The most widely used electrolyte to improve conductivity is sodium chloride (NaCl). An additional electrolyte is not required in leachate treatment because of its higher conductivity. Although electro-coagulation has proven a rapid and effective leachate treatment option, the significant generation of sludge with iron and other recalcitrant components is the typical dilemma of this method. Electro-oxidation is a form of oxidation using electricity. The electro-oxidation method applies a steady voltage or current to the compound to be processed. The whole process of electro-oxidation either directly or indirectly occurs at the electrolytic cell [217]. The polluting particles exchange electrons with the anode surface through direct oxidation. However, this process does not seem to be efficient for the organic compounds' degradation, although it expedites the formation of extremely strong oxidizing agents that are used in indirect oxidation. For higher chlorine concentrated leachate, indirect electro-oxidation is more effective.

The hypochlorite formed by the anode oxidizes the active chlorine, which has a powerful oxidation effect on organic compounds. This reaction is especially well suited to saline leachates, which contain several contaminants, such as ammonium, as well as metal ions (Ag+, Fe^{3+}, Co^{3+}, Ni^{2+}). Electrochemical oxidation removes up to 60% ammonium and 70% COD with energy consumption ranging from 0.377 to 0.740 kWh/L, depending on the treated sample [120]. The Boron-Doped Diamond (BDD) anode is a cost-effective electro-oxidation technique because of its fast oxidation, high current efficiency, and low energy consumption.

8.8.6 Ion Exchange

Ion exchange includes the exchange of anions or cations between pollutants and the exchange medium to extractions from an aqueous solution. It is a reversible ion exchange between the solid and liquid phases that do not result in any significant alteration in the solids internal structure. Ion exchange materials are usually made up of resins containing ionic functional groups and made from synthetic organic materials. These ionic functional groups are bound to exchangeable ions. Inorganic or natural polymeric fabrics might also be used [8].

8.9 Integrated Technology for Landfill Leachate Treatment

The majority of physicochemical treatments removed high quantities of particular pollutants from the leachate. However, due to delayed reactions in the process, as well as the production of intermediate matter or the disintegration of high molecular matter rather than being completely removed from the leachate, the removal of some types of pollutants is relatively low. As a result, for optimal pollutant removal, combining physicochemical approaches with biological treatment is recommended.

8.9.1 Integrated Coagulation Process

Coagulation is usually used as a pretreatment technique (except for biological therapy) to improve the removal capabilities of other treatments. Due to the remaining Al^{3+} and Fe^{3+} in the leachate after coagulation, the coagulation procedure prior to biological treatment will present a problem. However, after coagulation, the residual iron concentration in the leachate allows for further oxidation, particularly Fenton oxidation. By reducing the amount of iron added to the process, a high concentration of iron can react as an abundant supply of active radicals for an effective photocatalytic process at lower pH values, making the process easier and lowering the cost.

Before the electro Fenton procedure, coagulation has also been used as a pre-treatment. COD is removed at a rate of 85%, colour is removed at a rate of 99%, ammoniacal nitrogen is removed at a rate of 81%, phosphorus is removed at a rate of 98%, and all heavy metals are removed at a rate of 98% (except Cr and Fe). Following electro Fenton, Fe concentrations were higher, possibly due to the dissolution of iron electrolytes, and Cr removal efficiency was very low. By removing organic materials, the coagulation process, when used in conjunction with membrane processes, can improve the value of permeate flux. When compared to raw leachate, Trebouet et al. [115] discovered that coagulated leachate increased water flux by about 35% (from 3.2×10^{-5} m/s to 4.72×10^{-5} m/s). However, COD removal decreased, which could be due to the presence of Fe^{3+}, which could change the surface charge and structure of the NF membrane.

8.9.2 Integrated Oxidation Process

Oxidation techniques have been combined with biological treatment to reduce COD, which is mostly made up of a non-biodegradable molecule, and to improve the biodegradability of the leachate. In most cases, conventional biological treatment fails to remove ammoniacal nitrogen from the leachate. Ozone-produced compounds like acetate and oxalate, which are easily biodegradable but react slowly with ozone and the hydroxyl radical, can also be effectively eliminated using the biological process. As a result, combining these procedures can lessen the need for excessive oxidant usage to oxidize these chemicals. The ozonation process consumes more ozone than the combined biological/ozonation process, resulting in a 20% reduction in COD reduction due to ozonation alone, but a 40% reduction in COD removal during the nitrification reactor for the combined treatment even without the addition of ozone. Fenton oxidation, in combination with an anaerobic filter and an activated sludge process, can remove up to 1400–1800 mg/L of ammoniacal nitrogen and over 95% of COD [146]. Meanwhile, adding chemical oxidation to leachate with low organic content improved COD removal by 66% [113]. Ozone-based advanced oxidation methods can also be used as a pretreatment for further biological treatment because oxidation improves biodegradability and breaks down a large molecular molecule into smaller ones.

Since the oxidation process proved to be an effective pre- and posttreatment for biological treatment, various researchers have investigated the combination of oxidation and biological with recycling. Rather than undergoing an interaction with the hydroxyl radical in the oxidation process, a biodegradable component in leachate can be eliminated by the biological process utilizing this technique. Because it is only required for the removal of refractory matter, the consumption of an oxidant such as ozone can be reduced by limiting the hydroxyl radical's reactivity with the biodegradable matter. As the recycling process continues, microorganisms in the combined process will adapt to the removal of non-biodegradable waste, reducing the amount of ozone consumed. Non-oxidized chemicals that remain in the leachate after oxidation can also be removed using activated carbon adsorption.

8.9.3 Combined Adsorption Process

Few studies on the use of adsorption (activated carbon) and biological processes in the treatment of leachate have been published. In these studies, activated carbons are usually added as a suspension to the biological treatment system. In this way, activated carbon can act as an adsorbent as well as a temporary storage location for organic materials. Granular activated carbon may store refractory chemicals within its surface, allowing for a longer period of biological breakdown by associated microorganisms. Adsorption may also help refractory LMW transition to more biodegradable forms [86].

Cecen et al. [89] increased the efficacy of his activated sludge process by adding PAC dosages of 1000–3000 mg/L. PAC demonstrated effective removal improvement at a leachate ratio of 20–25% when landfill leachate was co-treated with municipal wastewater in the trials. The PAC aided not only in the reduction of residual COD but also in the reduction of sludge dewatering by improving floc formation by serving as a nucleus (measured in terms of specific resistance to filtration or SRF). According to Kargi and Pamukoglu [88], a 0.25 g/L PAC concentration added to activated sludge biological treatment could remove only 17% COD via adsorption. Increasing the activated carbon concentration in the biological treatment, on the other hand, will improve adsorption, whereas adding 2 g/L PAC to the biological treatment can remove 86% of COD in 30 h [88].

Because ozonation can break down high-MW compounds into low-MW compounds, which are better suited for adsorption by activated carbon, the adsorption process can also be used as a follow-up treatment after oxidation, particularly ozonation. Rivas et al. [124] discovered that activated carbon (30 g/L) could remove 90% of COD from leachate after ozonation in a 120-h operation with a COD/g AC ratio of 0.2. The treated leachate's biodegradability was increased to between 1.2 and 1.7, with high heavy metal removal of over 80% for Cr, Fe, Mn, Co, Ni, and Zn.

In the meantime, combining adsorption and membrane processes improved removal capacities while lowering membrane process energy consumption. To increase efficiency and achieve a high recovery rate comparable to that of a RO system, the adsorption process is usually combined with NF of UF. The combination of these processes will save money because UF and NF operate at lower pressures than RO and reduce fouling caused by impurities in the feed. The use of an adsorbent in the feed prior to the membrane process reduces permeate fouling, resulting in improved permeate quality and flow [92, 117]. The addition of activated carbon to the membrane layer minimizes fouling by creating an incompressible but high fluid permeability filter layer and allowing for continuous particle exchange [92].

8.9.4 Combined Membrane Processes

Membrane processes have been discussed in conjunction with other physicochemical processes. These techniques can be used with biological treatment in addition to physicochemical treatment. The feed is treated with biological treatments before it is treated with membrane procedures. Bohdziewiez et al. [113] found that employing NF methods could remove more COD and TOC from nitrified denitrified leachate than raw landfill leachate.

Trebouet et al. [115] reported similar greater removals, implying that removing low molecular mass compounds from the leachate via biological pretreatment can improve the removal effectiveness of membrane processing units. To fulfil the limiting concentrations for the effluents, current treatment facilities for leachate mostly comprise different treatment processes. All of the aforementioned combinations match the limiting criteria, have been in operation for a number of years and may be considered cutting-edge treatment facilities.

8.10 Conclusion

The most common leachate treatment, which includes biological BOD removal and nitrification/denitrification, is unable to remove the wide range of pollutants found in landfill leachate. In many countries, the treatment is unable to achieve the legal discharge level. As a result, several treatments for leachate treatment, including physicochemical processes, have been used to meet these standards. These physicochemical treatments have been described, as well as various researchers' investigations into their removal capacity in treating landfill leachate. These physicochemical and biological techniques have been used to treat both organic and inorganic materials in leachate. To improve removal efficiency, a variety of treatment process combinations have been used, resulting in effluent with a lower concentration than the discharge level. Some combinations, however, are prohibitively expensive, rendering them unviable and limited to highly toxic waste leachate. As a result, some of these physicochemical treatments would be better paired with biological treatments to compensate for each process's inability to remove organic and inorganic debris.

Glossary

Advanced oxidation process (AOP) Advanced oxidation processes (AOPs) are a set of chemical treatment procedures designed to remove organic (and sometimes inorganic) materials from water and wastewater by oxidation through reactions with hydroxyl radicals (OH). However, in real-world applications of wastewater treatment, this term usually refers to a subset of such chemical processes that employ ozone (O_3), hydrogen peroxide (H_2O_2), and/or UV light. One such type of process is called in situ chemical oxidation.

Dissolved air flotation (DAF) Dissolved air flotation (DAF) is a water purification process that removes oil and solids from wastewaters (and other water sources). Air is removed from water or wastewater in a flotation tank basin by dissolving it under pressure and then releasing it at atmospheric pressure. It is possible to remove the suspended matter from the water using a skimming device because of the bubbles formed by the release of air.

DNA DNA, or deoxyribonucleic acid, is a long molecule that carries our genetic code. It is like a recipe book for the proteins in our bodies, with step-by-by-step instructions.

Municipal solid waste (MSW) Municipal solid waste refers to waste that is either collected by the municipality or disposed of at a municipal waste disposal site, which includes items such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries. This comes from our homes, institutions like schools and hospitals, and businesses.

Sequencing batch reactor (SBR) Sequencing batch reactors (SBR) or sequential batch reactors are activated sludge processes used for wastewater treatment. SBR treat wastewater in batches, such as sewage or the output from anaerobic digesters or mechanical biological treatment facilities. Water and activated sludge are mixed with oxygen to reduce the organic matter (biochemical oxygen demand (BOD) and chemical oxygen demand (COD), respectively). In some cases, treated effluent may be suitable for discharge into surface waters or for use on land.

Van der Waal forces In general, it describes the attraction of intermolecular forces between molecules. Because of the electric polarization that other particles induce in each particle, only weak attractive forces act on neutral atoms and molecules.

Volatile fatty acids (VFAs) Volatile fatty acids (VFAs) are linear short-chain aliphatic mono-carboxylate compounds, such as acetic acid, propionic acid, and butyric acid, which are the building blocks of different organic compounds. Two to six carbon atoms are found in VFAs, which include acetic acid and caproic acid. Anaerobic digestion is tightly regulated by VFAs. Methane and carbon dioxide are produced as a result of the decomposition of organic matter.

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Chapter 9
Health and Safety Considerations in Waste Management

M. Shahrir M. Zahari, Izan Jaafar, Shahrul Ismail, Noor Zaitun Yahaya, Hamidi Abdul Aziz, and Yung-Tse Hung

Abstract Waste management is an essential element whether it is in developed or developing countries since each country needs to deal with waste products that involve the collection, treatment and disposal of the refuse/garbage. A part of effective management would include safety and health requirements since it will provide protection for the workers while reducing costs in terms of accidental and work-related diseases. Henceforth, health and safety scope play a crucial role for industries associated with high risk and accidental issues such as mining and construction, as would be available in most literature. However, it rarely includes the waste sector even though the workers are exposed towards various high-risk factors not just from the ergonomic aspect but also in the physical and mechanical element as well as biological and chemical risks. The so-called safety concern is revolved around the physical hazard during the whole management step of waste, whereas the health risk is particularly due to the bioaerosol elements (dust, bacteria, fungi, endotoxin,

M. S. M. Zahari (✉) · S. Ismail · N. Z. Yahaya
Environmental Technology, Faculty of Ocean Engineering, Technology and Informatic, Universiti Terengganu Malaysia, Kuala Nerus, Terengganu, Malaysia
e-mail: shahrir@umt.edu.my; shahrul.ismail@umt.edu.my; nzaitun@umt.edu.my

I. Jaafar
Environmental Science, Faculty of Science and Marine Environment, Universiti Terengganu Malaysia, Kuala Nerus, Terengganu, Malaysia
e-mail: izanjaafar@umt.edu.my

H. A. Aziz
School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Solid Waste Management Cluster, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
e-mail: cehamidi@usm.my

Y.-T. Hung
Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, OH, USA
e-mail: y.hung@csuohio.edu

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etc.) Even more, these health and safety issues in waste management are considered more obvious in developing countries than in developed countries since most of the waste is handled by hand/manually, and there is also a lack of awareness or consideration regarding the risk. Obviously, each country dealt differently depending on the technological advancement in which developed countries would have a wider scope involving waste risk, such as for technological waste treatment (e.g. composting and incineration) and management of quite riskier waste materials (hazardous or radioactive waste). Nonetheless, the health risk related to waste management needs to be assessed for both the exposure pathway (workers and public) and also on the health effect from the exposure, with the need to consider the confounding factors.

Keywords Bioaerosol · Biomarker · Composting · Epidemiological study · Incineration · Waste management

Abbreviations

1-OHP	1-Hydroxypyrene
8-OHdG	8-Hydroxy-2′-deoxyguanosine
CDD	Chlorodibenzo-p-dioxin
CDF	Chlorodibenzo Furan
CFU	Colony-forming unit
CI	Confidence interval
COMARE	Committee on Medical Aspects of Radiation in the Environment
dB (A)	Decibel (A)
DNA	Deoxyribonucleic acid
E. coli	*Escherichia coli*
ESP	Electrostatic precipitation
EU	European Union or endotoxin unit
HBV	Hepatitis B virus
HIV	Human immunodeficiency virus
HxCB	Hexachlorobenzene
IgE	Immunoglobulin E
I-TEQ	International toxic equivalent quantity
KIM-MHO	The key indicator method for manual handling operations
MAC	Maximum allowable concentration
MSW	Municipal solid waste
N	Newton unit
NIOSH	National Institute of Occupational, Safety and Health
OD	Odd risk
OSH	Occupational safety and health
PAH	Polycyclic aromatic hydrocarbon
PCBs	Polychlorinated biphenyls
PCDDs	Polychlorinated dibenzodioxins

PCDFs	Polychlorinated dibenzofurans
PeCB	Pentachlorobenzene
qPCR	Quantitative polymerase chain reaction
RR	Relative risk
SNPs	Single-nucleotide polymorphisms
TCB	Trichloro benzene
TCDD	2,3,7,8-Tetrachlorodibenzo-p-dioxin
TEF	Toxicity equivalent factor
TLVs	Threshold limit values
UK	United Kingdom
USA	United States of America
VLI	Variable lifting index
VOC	Volatile organic carbon
WHO	World Health Organization

9.1 Introduction

It is the economic productivity and the social consumption that eventually create municipal solid waste as one of the residual outcomes. Waste sources varied across a wide scope of human activities that included residential housing, business premises, institutions, industries and markets. Considering that both the urban and rural demographic growth and economic progress inevitably increase the amounts of solid waste, it henceforth brought about increasing environmental and general population on its management and disposal. This activity of solid waste management emphasises a huge range of activities that commonly start from the collection process of the garbage for disposal; collection and sorting for the materials (especially the recyclable one); collection and treatment of commercial and industrial waste before moving towards the final disposal point of the garbage. From every single step of that solid waste management process, risks are present, starting from the beginning, which is a source of collection (e.g. at homes), during transportation/handling of the different waste materials and at the sites of the recycling process or final disposal of waste. Individuals directly involved in those steps are exposed to occupational health and accidental risks related to the content of the materials/the waste materials that they had to handle, exposed to the emissions from those refuse and the equipment being used either as light or heavy-duty appliances.

Depending on the source from where the waste came from, infectious medical wastes and toxic industrial wastes, which are not properly segregated and getting mixed along with waste from domestic sources, will expose the waste collectors to a wider array of risks. There is a possibility that most diseases (being water borne, airborne or upon contact) have exposure pathways within the solid waste management practices, and most injuries inflicted during waste handling have contact pathways that can lead to hepatitis B virus (HBV), human immunodeficiency virus (HIV), tetanus and so much more. As a result of their exposure to multiple risk factors, they have the likelihood and tendency to suffer from occupational health problems. However, these risks can be eliminated or at least minimised by making waste technologies and practical more contained, thus direct and indirectly reduced contaminant emissions. A simple action such as changing working methods could produce interference/interrupt the pathways (e.g. using protective clothing or gloves).

In developing countries, the waste being thrown out for collection is seldom stored in closed containers because of either the poorly maintained trash bin or overflowing, which would cause the waste to be piled on the ground, thus requiring that it be shovelled or handled physically by hand. This uncalled situation leads towards direct contact and possibility, increasing the risk for workers to those exposed to solid waste, rather than their counterparts in high-income countries, who predominantly handle sealed plastic bags and covered dustbins. Moreover, the exposure to health risks within most of the developing countries are not even being considered as a special occupational problem, especially not in the solid waste management sector. Even in most high-income countries, the data regarding health and accident consequences in relation to solid waste handling is still inadequate, and even more so in developing countries where the data alone is almost non-existent. And so, very little importance is being imparted into this sector for developing countries like India, where there is even a very small or relevant study of the health and injury incidence pertaining to the workers involved in the solid waste practice.

Most of the reviewed studies conducted on this matter in both developed and developing countries are lacking due to various limitations related to poor exposure assessment and lack of information on relevant confounders either in the management part or on the lower-level workers. After all, waste-related work is overridden by the general public, causing both social and economic as well as environmental deprivations towards the solid waste workers, and sometimes also involves gender issues. These gender issues are particularly common for women sweepers since they are in poor condition in working environments, such as having no protective wear or equipment while they are working. To the dismay, there are hardly any complaints about the situation, indicating how poor the awareness on safety knowledge.

9.2 Health and Safety Issues in Waste Management

Every step of the waste handling, treatment and all the way towards final disposal can be associated with health issues of waste, which can be either directly via occupations in the waste management industry/processing steps included in the recovery and recycling activities or by exposure to certain hazardous substances mixed purposely or accidentally in the waste stream or to the emissions being released from the waste processing such as incinerators and landfill sites. The exposure could be either directly (e.g. vermin, odours and noise) and/or indirectly (e.g. via ingestion of contaminated water, soil and food that had come into contact with the waste materials). In the past, epidemics associated with water were especially due to contamination with pathogens that caused cholera disease that decimated the population of

Europe, and even now, the disease still remains a common occurrence. During that time, the link between the source and the outcome (disease) was discovered for action taken to prevent the spreading of the disease. This is possible because visual observation is applicable for some of the direct health impacts from the waste that is poorly managed. After all, it is quite well known that environmental impacts due to the emission during waste management activities are associated with municipal solid waste. Even with such knowledge, any conclusive detail is incomplete. The issue is very subjective, as well as the involvement of a huge range of possibilities for both the direct and indirect risk/health impacts from every aspect of the waste management activity.

When it comes to health issues, the main pathways of exposure are primarily through direct inhalation (especially through contact with emissions from landfills, incinerators or any other waste treatment process). Another type of exposure is from the consumption of water (most likely to occur if the water supplies close by or connected through natural stream line being contaminated with landfill leachate) and/or consumption by the mean of the food chain (especially consumption of harmful bacteria and viruses from the contaminated food source in which the microbes being carried over by vector or vermin from the sewage and manure). Our current lifestyle also exposes us to persistent organic chemicals that might accidentally be consumed through food enriched with such substances released as combustion emissions from incinerators. In the case of exposure to ionising radiation, the surrounding population might be affected by natural background exposure (around 2–3 mSv per year) [1, 2]. In some parts of the world, background exposure can be a lot higher, primarily due to the high levels of thorium, uranium and thorium in the site's mineral bedrock. This also usually occurs, especially when radon gas tends to accumulate indoor or inside mines (up to a few thousand of mSv per year). However, it is very advisable that the maximum recommended occupational limit is at 100 mSv [3] over a period of 5 years (i.e. an average of 20 mSv per year) and strongly avoid so that there is no more than 50 mSv in any one of these 5 years. Table 9.1 shows the recommended limit of dose and baseline for employees and the general population public from a point source for preventable situations [4] and the dose limits being recommended for planned exposure situations or work-related in Table 9.2.

Rather than direct health effects, the indirect health effects from waste disposal activities could subsequently come in the form of greenhouse gasses contribution. After all, greenhouse emission sources in the EU recognise one of the main contributions to be the methane released from landfills produced through anaerobic decomposition of biodegradable waste [5]. It is likely that both old and young people diagnosed with asthma or any other respiratory problems, and especially elderly folks suffering from any type of cardiovascular problems, would be more affected by rising temperatures and also by the ground-level ozone levels. Another indirect effect would be on the spread of diseases (e.g. malaria) through vectors such as mosquitoes or rats becoming more common, especially as the waste column could become a perfect breeding area. Unlike health effects, occupational accidents can be relatively common in the waste industry as they would in another industry, but it is found that accident risk in the waste management sector is much higher than the national average for other occupations [6]. Henceforth, the potential cases of

Table 9.1 Recommended limit of dose and baseline for employee and the general population public from a point source for preventable situations [4]

Bands of constraints and reference levels (mSv)	Characteristics of the exposure situation	Radiological protection requirements	Examples
1 or less	Exposure to receptors (individuals) to a single source that would provide a very minimal outcome personally but benefits greatly to the society in general. Exposures are usually controlled by action taken directly from the source, in which cases such as radiological protection requirements can be planned in advance	General information on the level of exposure should be made available. Periodic checks should be done on the exposure pathways as to the level of exposure	Constraints set for public exposure in planned situation/scenario
Greater than 1–20	Individuals will usually receive benefits from the exposure situation but not necessarily from the exposure in itself. Exposures may be controlled at source or, alternatively, by action in the exposure pathways	Where possible, general information should be made available to enable individuals to reduce their doses. For planned situations, individual assessment of exposure and training should take place	Constraints set for occupational exposure in planned situations. Constraints set for comforters and carers of patients treated with radiopharmaceuticals. Reference level for the highest planned residual dose from radon in dwellings
Greater than 20–100	Individuals exposed by sources that are not controllable, or where actions to reduce doses would be disproportionately disruptive. The pathways are controlled as a way to limit exposure	Minimising the doses could be put into consideration. The dose should be reduced with more effort as it is approaching 100 mSv. Individuals should be informed about the radiation risk and the prevention steps taken to reduce the doses. The doses for each individual should be taken for assessment purposes	Reference level set for the highest planned residual dose from a radiological emergency

Table 9.2 Dose limits recommended for planned exposure situations or work-related [4]

Type of limit	Public	Occupational
Effective dose	1 mSv a year	20 mSv per year, averaged over defined periods of 5 years
Annual equivalent dose in:		
Lens of the eye	15 mSv	150 mSv
Skin	50 mSv	500 mSv
Hands and feet	–	500 mSv

exposure and also for the adverse effects to the resident population are most likely to be higher compared to the ones investigated by epidemiological studies.

9.3 An Epidemiological Study in Waste Management

Based on the work carried out by Saffron et al. [7], the quality of the epidemiological studies can be classified on the basis of the following criteria, which includes:

1. Epidemiological study design (either prospective cohort studies and/or experimental studies)
2. Sample size and statistical analyses
3. Confounding factors (consideration towards other sources of pollutants from both indoors and/or outdoor sources)
4. Availability of exposure data (in relation to factors such as distance from waste management facilities)
5. Inclusion of information on the site waste management procedures/practices (it will influence the level of a pollutant as well as become the pathways or exposure route)
6. Research relating to human activities/general public or exposure aspects (totally different when it comes to animal studies which are usually in the wild or lab-based)
7. The degree of the connection that would be the core link in between the probable cause and effect, referring and translating into the value of 'relative risk'.

9.3.1 Designing an Epidemiological Study

For activities associated with waste management, the type of epidemiological research would be focused on the health effect on the human body, whether adverse health or injuries, so the data would primarily be obtained through 'observational' rather than 'experimental' work (Fig. 9.1). This is also likely since it would be unusual and definitely unreasonable to do experimental work with regard to human subjects as compared to an animal as the target receptor.

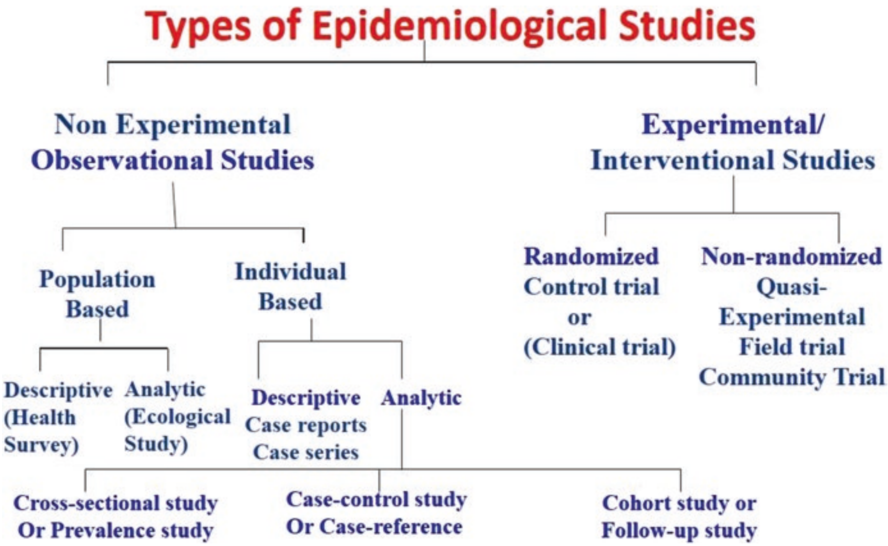

Fig. 9.1 Types of epidemiological studies [8]

Moreover, experimental research involving human subjects is mostly related to studies such as the clinical trial phase for the development of new products, which are also intended for human usage. Pharmaceutical industries usually conduct and fund this kind of trial which voluntary test group or population. The known group will be induced or asked to try out a certain new/specific substance or drug, and the result would be compared to a control group or population which are not exposed to the new substances/drugs. The hypothesis would be to inspect positive feedback from the test group compared to the control one, such as better health response due to new vitamin intake or better health outcomes (e.g., lower blood pressure) from the use of hypotensive drugs. As opposed to these experimental types, the typical types of observatory investigations are the following:

1. Prospective cohort studies:

   In this study, two separate groups of people or populations recognised as either an exposed population or non-exposed would be identified and analysed for a certain period of time. Monitoring of health effects or any target developed risk would be taken and kept track for both the groups of people, and surveys or other kinds of information would also be collected during the study time period. Collection and analysis of human tissues (e.g., blood, hair, teeth or urine) are the common types of samples taken in order to evaluate the level of exposure and disease spreading or development rate. Unfortunately, considerable huge populations are needed to rule out the confounding factors as possible interfering parameters and to ensure that the result is statistically significant, but this in itself would definitely incur quite a considerable amount of overall cost.

2. Retrospective case-control studies:

   In this case, a group of healthy people would be taken as control, while another group of people (specifically the patient) is selected in which a particular disease has already developed within the patient. Information on past exposure will be collected, and all the involved participants will be interviewed.

   Lesser cost is expected from these studies than the prospective cohort studies since the participants still comprise a group of people but in a much smaller size hence requiring fewer investigators. However, they would be more prone to bias due to small groups compared to the prospective cohort studies.
3. Cross-sectional studies:

   This study was carried out in a relatively lesser or shorter period of time and only involved a specific subgroup of the exposed population. Since they are totally different from the longitudinal studies, the findings are more useful to generate hypotheses, and it needs more comprehensive studies for further clarification.

   A common illness could be effectively investigated by these methods since it is a much cheaper option, but the lack of information makes it difficult to distinguish whether exposure to a potential hazard is the main reason for the particular illness is developed.

9.3.2 Sample Size and Statistical Evaluation

Usually, the investigation of the environmental epidemiologists would be related to a certain population where the clinical effects occur influenced by emissions at slightly above natural background levels. The difficulty would arise, especially where sanitary landfills, incinerators, or other waste management facilities are in full compliance with legislation/guidelines, having been built with the best available, state-of-the-art technology. In this case, the study must have an adequate sample size capable to detect significant clinical differences which had a very probable chance of a relationship between the test population and a control population. This would prevent a false conclusion, either a positive or a negative one. Obviously, the investigation power relies heavily on sample size since the two populations are usually small, which would make the detection of clinical effect quite unclear; thus it would normally require the epidemiologist to assess at least a large number up to tens of thousands of people in both the control and exposed population, which might even require more population sample than the one existed in the study area. Other than that, epidemiological studies might also contain other types of limitations, which include:

1. Confounding factors (e.g. race/nationalities, lifestyle, the risk from other sources)
2. Insufficient data on direct exposure or emissions of the sources, whether it is truly coming from the waste management facilities and other sources
3. Mobility/movement of the population
4. Illnesses that might have a long period of latency

9.3.3 Exposure Data

At waste management facilities, exposure to a worker on a certain substance usually results in either:

1. Acute—related to the high levels of potentially harmful substance that would result in a very serious accident even though the exposure occurred in a short period of time, most likely to occur if the substance were to be ionising radiation or active bioaerosols/dust compounds
2. Chronic—related to low levels of these harmful substances or radiation, but with exposure occurring during a long period of time

Defining the strength that connects together the specific health effects that arise due to exposure to a potentially harmful substance is an important step in an epidemiological study. This is achieved by making a comparison between the exposed and the control population. For the exposed population, the ratio of the disease incidence is calculated and is compared to the same disease incidence in the non-exposed population or commonly referred to as relative risk (RR). Meanwhile, odd risk (OR) refers to a similar index of associations but in case–control studies. The value of RR > 1 is an indication of the risk increment for the specific health outcome to develop. For example, the risk is an increase up to five times higher if the RR value is 5, which also means that it is 400% more than usual.

Though a certain disease is discovered to have an increased risk of more than one times or RR > 1 for a specific exposure scenario, the primary cause of the health situation could be more than just the one currently being investigated. Consideration of many other issues is required to evaluate whether the specific substance is the only cause for the health effect or disease. As such, the statistical significance of the interaction/relationship is required as it would exclude the chance that it might occur due to other factors. Occasionally 99% confidence level (confidence interval) is required, but sometimes even those of 95% is already acceptable. In Table 9.3, the model for the definition of the strength of evidence that correlates between the exposure and certain illness used by both the World Cancer Research Fund and the American Institute for Cancer Research [9] is being presented. The combination of the value of specific RR and statistical significance is expressed in terms of the risk level. High RR values mean that there is a strong link between the adverse health

Table 9.3 The value of relative risk (RR) and odds ratio (OR) [9]

RR or OR	Strength of evidence	Statistical significance
>2	Strong	Yes
>2	Moderate	No
1.5–2.0	Moderate	Yes
1.5–2.0	No association	No
0.87–1.5	No association	No

effects that in relation to some environmental factors. However, the majority of epidemiological studies on health/bio risk aspects with possibilities associated with waste management activities rarely give a report on RR or OR values greater than 2, and most would be less than 1.5, as shown in Table 9.4.

9.3.4 Biomarkers

Exposure of a person to the total amount of toxicant does not necessarily mean that it would cause any adverse effects. In fact, the amount of toxicants that become bioavailable or adsorbed by a particular body part (organ, tissue or cell) may eventually create a specific health outcome or cause a toxic adverse effect. Even then, there is also the likelihood that different individuals will respond to varied depending on certain physical factors such as gender, age and genetic susceptibility for a known exposure dose. This happens to be the very limitation of epidemiological studies that tried to correlate the dose–response relationship and the attempt to compare those outcomes with the exposure data or information obtained from a single point or diffuse sources. The difficulty increases if the study attempts to represent upon exposure to a population further away from a waste management facility. It became complicated since pollution such as leachate from a poorly engineered or operated landfill that contaminated the water (surface water or groundwater) by introducing toxic pollutants into the water body which could be considered as a sort of exposure, but it is still not conclusive enough to be related to the surrounding residential population since that residence might actually obtain drinking water from another waste source or from another region elsewhere.

Realising this predicament, biomarker epidemiology has been developed as a new yet very important approach to complete the unclear relationship between the environmental assessment and the health status, which is the very core of epidemiological investigations weaknesses. By definition, biomarkers refer to certain biological indices or indicators that can be employed as a means to measure the degree of exposure at either cellular or molecular level and relate it to known effective doses of harmful compounds and their adverse effects. Generally, biomarkers are categorised into three groups known as:

1. exposure to biomarkers,
2. health effects biomarkers, and
3. susceptibility of biomarkers.

Xenobiotic compounds or metabolites present within the human body are usually used as exposure biomarkers. The substances chosen might also be the type of compound that is produced naturally when there is an interaction among the metabolites or xenobiotics with other compounds that exist in the body. Their concentration and presence are quite commonly measured within the human body tissues (urine, blood, serum, urine, teeth and other types of tissue or could even be in the human

Table 9.4 Association between health and environmental factors being expressed in the unit of RR or OD values to the link between the receptor to the health and well-being of waste management facilities [10–21]

Cause	Effect	RR or OR	CI
Landfilling			
Nant-y-Gwiddon, UK	Congenital anomalies		
	Before site opened (1983–1987)	1.9	1.3–2.9
	The first 2 years of operation (1988–1989)	3.6	2.3–5.7
	From 1990 to 1996	1.9	1.2–3.0
9565 UK landfill sites	Congenital anomalies	1.01	1.01–1.02
	Low birth weight	1.04	1.03–1.05
	Cardiovascular defects	0.96	0.93–0.99
Incineration			
Besançon incinerator, France	Non-Hodgkin's lymphomas	1.27	1.1–1.4
	Soft tissue sarcoma	1.44	1.1–1.9
13 incinerators, France	Non-Hodgkin's lymphomas	1.12	1.002–1.251
Incinerators and other industrial sources of dioxins, Italy	Sarcoma: Population with the highest exposure	3.30	1.24–8.76
Sewage contaminated water			
Sydney beaches, Australia	Gastroenteritis, from exposure to:		
	0–39 Faecal streptococci/100 mL	1.0	
	40–59 Faecal streptococci/100 mL	1.91	1.60–2.28
	60–79 Faecal streptococci/100 mL	2.90	1.43–5.88
	80+ Faecal streptococci/100 mL	3.17	1.12–8.97
	Any symptoms[a], from exposure to:		
	10–300 cfu/100 mL	2.9	1.7–5.1
	300–1000 cfu/100 mL	3.8	2.1–7.1
	1000–3000 cfu/100 mL	5.2	1.7–16.0
Exposure to ionising radiation			
Nuclear industry workers	All cancers excluding leukaemia	0.97[b]	0.14–1.97
	Leukaemia, excluding chronic	1.10[c]	<0–8.47
	Lymphocytic leukaemia	1.93[b]	
		1.19[c]	
Environmental factors			
Hepatitis B virus	Liver cancer	104	51–212
Cigarette smoking			
1–14 cigarettes	Lung cancer	7.8	Not available
15–24 cigarettes	Lung cancer	12.7	Not available
>25 cigarettes	Lung cancer	25.1	Not available

[a]Cough, eye or ear symptoms, fever, gastrointestinal symptoms; *cfu* colony-forming units
[b]For a radiation dose of 1 Sv
[c]For a radiation dose of 100 mSv

breath biomarker [22]. These exposed biomarkers provide a measurable indicator of the amount of harmful substances absorbed by each personnel.

Different from exposure biomarkers, health effect biomarkers reflect on the abnormal functioning of a specific organ or of the body itself, which usually occur upon exposure to a group of compounds (non-specific biomarkers) or upon a very specific compound within its group (specific biomarkers). This would enable evaluation and assessment of whether the impact of absorbed toxicants would be temporary/reversible or permanent.

Meanwhile, parameters that could either be physical, chemical or genetic, which are capable of making an individual become more sensitive to a toxic compound and pose higher health risks from exposure, are so-called susceptible biomarkers. An example of a susceptible biomarker would be an inherited gene disparity such as single-nucleotide polymorphisms (SNPs) capable of heightening or lowering disease susceptibility when being exposed to a certain environmental or chemical exposure [23].

This approach using biomarkers would enable detection at the beginning stage (could be at molecular or/and cellular level) of clinical variations linked with exposure to chemicals/substances and radiation. In this manner, the measurement of genetic abnormality (e.g. chromosomal irregularity in lymphocytes) and cell multiplication indices can be used as a susceptible biomarker for early detection of the relationship between exposure to harmful waste and DNA changes/damage [24]. Table 9.5 lists some studies conducted using biomarker approaches.

Table 9.5 Examples of studies conducted using biomarkers for waste pollutant/activities

Biomarkers	Exposure/correlation	Industry	Reference
Renal disfunction	Correlate positively with Pb concentrations	Pb smelter	[25]
DNA damage	Correlate positively with urinary metabolites of volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs)	Not available	
1-Hydroxypyrene (1-OHP) urinary metabolite	Exposure to PAHs: Exposed receptors showed a 1-OHP level of about 0.28 μmol/mol creatinine and 0.078 μmol/mol creatinine in the control groups (unexposed)	Not available	[26]
Serum and urinary estrogen metabolites	The increment of dioxin concentration is proportional with creatinine level as dioxins seem to metabolise estrogens to 16-hydroxyestrogens	Waste incinerator	[27]
Oxidative stress markers for the measurement of blood and urinary	There is a significant increase of 8-OH-dG in urinary obtained from employees exposed to fly ash, and the fly ash is detected to have PCDDs, PCDFs, PAHs and heavy metals	Municipal solid waste incinerator	[28]

For this scope of the study, the standard of current environmental surveillance is not sufficient because biological effects or changes can be measured only when the disease/infection are diagnosed, in which case the biomarker came to be a very useful indicator. Biomarkers enable the assessor to evaluate the level of excess exposure and assess the differences at the molecular and/or cellular level before a possible worst effect reaches the clinical stage. By gaining such information beforehand, adequate preventive action in a timely manner can be implemented to reduce possible risks.

9.4 Health Effects of Waste Management Activities

9.4.1 Waste Collections and Recycling

The safety and health status of the waste management industry differ significantly across the world, especially with strong disparity, and major variations are even more obvious between developed and developing countries. In developed countries, the likelihood or potential for any fatal or major accident is substantially subset by the workers or employee protections that impose stringent safety and health measures. But despite this stringent enforcement, it still exhibits a quite serious case for health and safety in the waste sector. For example, in the UK, the waste management sector consists of more than 160,000 workers, and every year, accident cases in this sector are about 3800–4300 in total [6]. The value of accident rates within the waste management system is four times higher than the national average for other occupational sectors. Based on that total value, the fatal injury accident rate is even higher, which is 10 times the national average, which puts the likelihood of about 10 per 100,000 waste management workers being exposed to fatal injuries. While the other major injury rate is still higher (three times higher than the national rate), this puts about 330 per 100,000 waste management workers at risk of experiencing major injuries.

Generally, most accidents are associated with sprain injuries due to waste handling or the possibility of being struck by the waste collection vehicles, as these activities occur during waste collection and loading/unloading of waste materials [6]. As for the impact within the recycling process, epidemiological studies on this scope are extremely rare and scarcely reported. Hence, a study in this field is crucially required since there is a significant increase in the recycling rate in waste practices for both developed and developing countries. In developing countries, unregulated or informal recycling practices, commonly known as waste scavenging in open dumps, remain a major issue that is associated with infections and injuries within the waste management sector.

9.4.2 Landfilling and Land Spreading

Types of ill health, such as increased birth defect risk and some cancers, especially for the communities surrounding landfill sites, have been suggested related to the close proximity or exposure to waste landfills. One of the major published findings was from The World Health Organization two workshops: the early one focusing on the health effects of waste landfills [29] and the latter version [30] looking upon the health effects of landfills and also on incineration. These two workshops conclude that the outcome, which is health endpoints (especially reproductive outcomes, cancer and even mortality) and the evidence which conclusive links or related those outcomes to waste landfills and incinerators to are either inadequate or insufficient.

Two major multi-site pieces of research conducted in the UK, which included about the majority of 80% UK population that lived in the proximity of about 2 km from 9565 landfill sites (774 categorised as special while the other 7803 were non-special and the rest 988 are unclassified) between 1983 and 1998 were conducted by Elliott et al. [12] and Elliott et al. [13]. However, there is still an unclear cause for the slight excess risk of birth defect and low birth weight due to the influence of confounding factors. Consequently, another study could not link the excess risk to the birth of a child with Down syndrome within the population nearing 6289 landfill sites in Wales, England, and the UK [31]. Some reports conducted by Fielder et al. [14] in the case of Nant-y-Gwiddon landfill sites in the UK exhibit the potential for congenital anomalies to be of high relative risk (RR). However, there is a lack of essential confounding factors since the local populations themselves had for quite some time been so close to certain local incinerators, which had been highly emitting pollutant emissions long before the landfill started operation [32].

9.4.3 Incineration

The burning process of an incinerator is capable of producing numerous potentially concerning pollutants, but one of the major health-related emissions would be ‘dioxin’, which is a group of persistent organic compounds. The group comprises numerous specified substances such as polychlorinated biphenyls (PCBs), polychlorinated dibenzofurans (PCDFs) and also polychlorinated dibenzo-p-dioxins (PCDDs). These compounds are mostly produced by the incomplete combustion of household waste, municipal waste, medical waste or even during forest fires, burning wood and coal, during the manufacture of pesticides and other chemicals and even found in a common daily item such as in tobacco smoke and car exhaust [14, 33]. The reason why these pollutants are of serious concern is due to their persistent nature (not easily biodegradable) and tend to accumulate in food products (dairy products, eggs, fish, animal fat). Many of these ‘dioxin’ (29) are considered to be quite toxic [34, 35], whereas 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) is the most toxic (carcinogenic), according to the International Agency for Research on

Cancer [36] after being evaluated on cohort studies of groups living in industrial areas and also on laboratory experiments.

Toxicity equivalent factor (TEF) units are used to define the toxicity of dioxins in which the TEF of TCDD (the most toxic) is rated as 1 and the others less than 1 (Table 9.6). Herein, the international toxic equivalent quantity (I-TEQ) represents the final toxic equivalent quantity in which the TEF value of each dioxin is multiplied by its concentration and is assumed that the effect of various dioxins is additive. The first inventory of 1993–1995 non-industrial as well as industrial emission sources of PCDDs and PCDFs in 17 European countries (EU 15 plus Sweden and Switzerland) were produced by Quaβ et al. [37]. The study shows the limitations experienced by health impact researchers due to the huge range of possible sources despite some questionable issues due to either the lack of data or the weakness of some of the original data, in which some of the confounding factors in epidemiological studies were present.

Figure 9.2 shows a summary of the main sources of PCDDs and PCDFs in 1993–1995. MSW incinerator, along with clinical waste incineration, happens to be the main source of PCDD/PCDF emissions to air, while 38% of the total emission comes from the sinter plants for recycled materials and residential wood combustion. Pollution control technologies have significantly reduced the emissions from

Table 9.6 Dioxin toxic equivalency factors (TEFs) as listed by the World Health Organization (WHO)

Compound	Specific name	TEF
Dioxins	2,3,7,8-Tetra-CDD	1
	1,2,3,7,8-Penta-CDD	1
	1,2,3,4,7,8-Hexa-CDD	0.1
	1,2,3,6,7,8-Hexa-CDD	0.1
	1,2,3,7,8,9-Hexa-CDD	0.1
	1,2,3,4,6,7,8-Hepta-CDD	0.01
	OCDD	0.0001
Dibenzo furans	2,3,7,8-Tetra-CDF	0.1
	1,2,3,7,8-Penta-CDF	0.05
	2,3,4,7,8-Penta-CDF	0.5
	1,2,3,4,7,8-Hexa-CDF	0.1
	1,2,3,6,7,8-Hexa-CDF	0.1
	1,2,3,7,8,9-Hexa-CDF	0.1
	2,3,4,6,7,8-Hexa-CDF	0.1
	1,2,3,4,6,7,8-Hepta-CDF	0.01
	1,2,3,4,7,8,9-Hepta-CDF	0.01
	OCDF	0.0001
Coplanar PCBs	3,3′,4,4’-TCB (77)	0.0001
	3,4,4′,5-TCB (81)	0.0001
	3,3′,4,4′,5-PeCB (126)	0.1
	3,3′,4,4′,5,5’-HxCB (169)	0.01

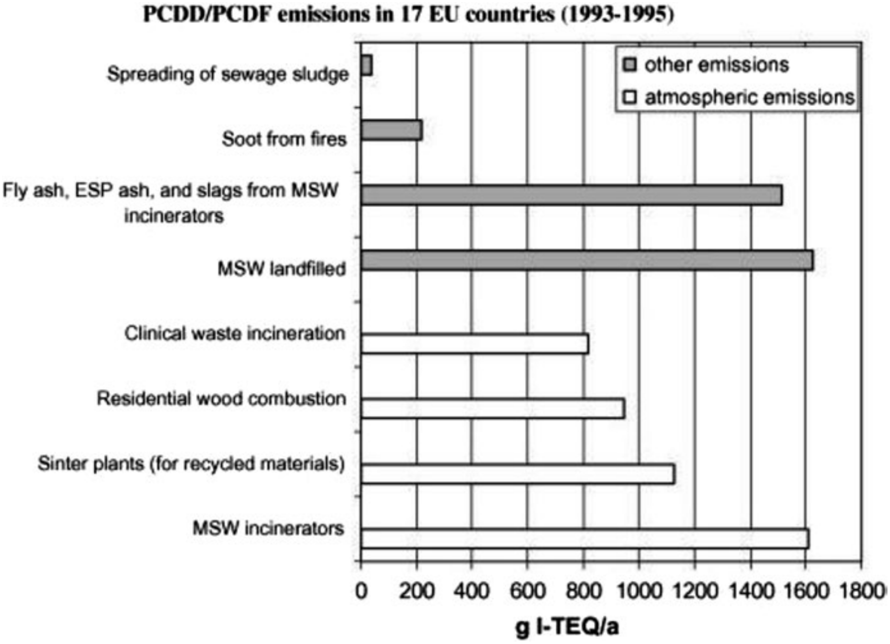

Fig. 9.2 Main emissions of PCDDs/PCDFs from waste activities during the year 1993–1995 among the 17 EU countries [37]

MSW incinerators since the EU set an emission limit (0.1 ng/m^3 I-TEQ) for incineration plants and being complied by all incinerators in some EU countries. The total atmospheric emissions would be reduced to about 20 g of I-TEQ annually if all EU incinerators complied with this requirement [37].

Epidemiological studies around MSW incinerators are often related to diseases such as non-Hodgkin's lymphoma and soft tissue sarcomas. Countries with the largest number of incinerators in the EU, such as France, have carried out various studies on these diseases, particularly since the Besançon incinerator [19] was constantly contributing towards the dioxin emissions quite excessively, along with about 13 other French incinerators [20]. Based on the residence and soil levels of dioxins, a link between non-Hodgkin's lymphoma and exposure to dioxins being emitted by the municipal solid waste incinerators was found, even though the strength of this association was weak. Meanwhile, in the USA, conclusions were made by the National Research Council [38] that epidemiological studies could not detect any significant excess health effects. A causal relationship could not be determined even though most researches reviewed by Hu and Shy [39] had shown organic chemicals at quite a high level together with the heavy metals concentration in the populations residing closer to incinerators. A total of 102 publications included in a review by the Department of Environmental Food and Rural Affairs [40] even concluded that there is no convincing evidence of a link between landfill and cancer or between incineration and respiratory problems or cancer.

9.4.4 Composting

In regard to waste bioprocessing such as composting, there is definitely insufficient information regarding pathogens after inputs of biosolids/compost that are incorporated in the soils. Evidently, there are various types of bacteria/pathogen such as *Escherichia coli*, *Salmonella*, *Giardia*, *Campylobacter* and *Cryptosporidium* [41] and viruses within the manure (from animal waste), sewage sludge and compost, but the fate of these pathogens are unknown within the solid or compost. However, there has been an exponential increase in cases being recorded for food poisoning, and the most likely cause was the detection of *E. coli* O157 within the agricultural soil where the application of organic waste was practised [42]. Even in most and different parts of the globe, both the freshwater and marine water contamination incidents have been linked together to the sewage treatment plants discharges as well as the manure where it is used for land application as organic soil amendments materials [43]. The spread pathways are not only limited to bioaerosols but also through bacterial and viral contamination of surface water from runoff [44]. Figure 9.3 shows possible exposure pathways of the composting process to both the worker and also the surrounding population [45].

Instead of pathogens, compost workers are more concerned about developing respiratory and dermal illnesses than the general public [46–49], especially since most household waste and green waste composting is treated using open-air windrow systems/methods with just some slight shift towards plant-vessel. The most highlighted publication found in the chemical and biological risks of composting workers facilities and nearby local residents is done by Domingo and Nadal [45]. The study recommended that any compost that has possible health risks for the population should not be commercialised.

As for atmospheric exposure to both the workers and general population, the cause of the concern is primarily towards respiratory illnesses due to the exhalation of dust, microbes (bacteria, fungi and actinomycetes) and compounds (endotoxins and $\beta(1 \rightarrow 3)$-glucans) released at composting facilities; since few studies were found related to impact from bioaerosol dispersion. The latest scientific study that can be found regarding this matter in the Medline database during the recent 10 years period (2010–2020) is related to the study conducted for three composting facilities using different waste materials which is domestic, manure and carcass, whereas the study itself used two different quantification methods (cultivation and qPCR) for the determination of moulds and bacteria concentrations. It was concluded that there was a possible occupational health risk to the compositing workers due to contact with aerosolised pathogens such as *Mycobacterium* and *Legionella* and, more specifically, *L. pneumophila*. For those working in this kind of atmosphere, it is proposed that TLVs (threshold limit values) of 10,000 colony-forming units by the cubic metre (CFU/m^3) of air for the total bacteria to avoid biorisk and a much lower value which is 1000 CFU/m^3 of air for the Gram-negative bacteria [50]. This is because endotoxins produced by the Gram-negative bacteria cause not only respiratory problems but could also lead to fever, diarrhoea and gastrointestinal

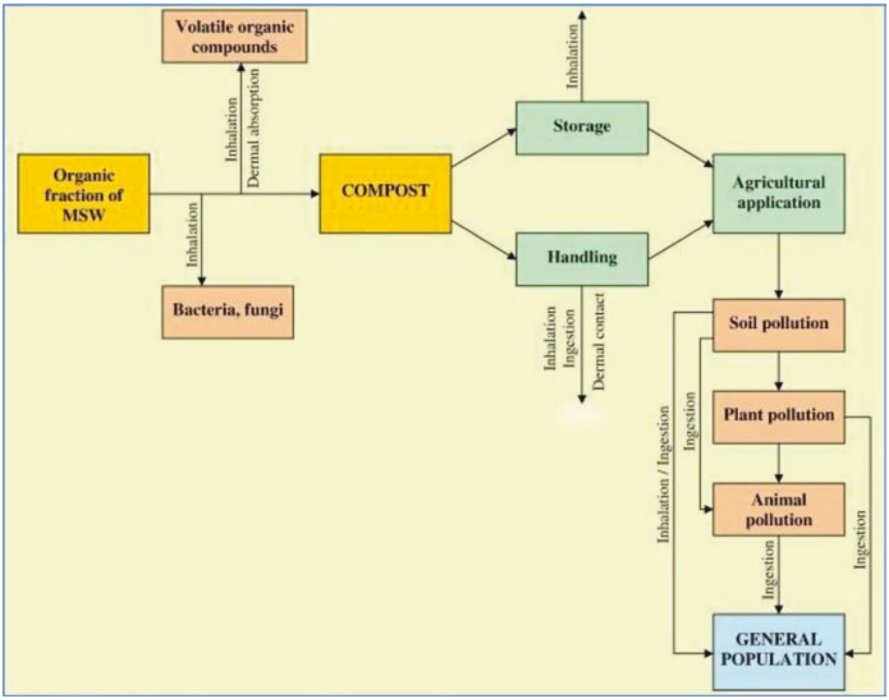

Fig. 9.3 Pollutant exposure pathways generated from the utilisation of MSW organic fraction towards the production of compost [45]

disturbances [51]. Other than these latest published studies, examples of other studies related to the health risk from composting are listed in Table 9.7.

9.4.5 *Clinical/Radioactive Waste*

Most studies on clinical and radioactive waste were resolved upon reported clusters of leukaemia in children residing close to nuclear plants or nuclear-reprocessing facilities, especially in Europe (carried out in the UK and France). However, most of these studies could not bring full proof of evidence of a relationship between the occupants near the nuclear sites and negative health outcomes. The finding using a case–control method by Gardner et al. [63] showed results on the leukaemia and lymphoma sickness among younger generation around the Sellafield nuclear power plant in the UK that could cause some discerning issue, but upon a further study by COMARE [64] had concluded that cause–effect relationship between the radiation and the health effect has invalid statistical significance. Meanwhile, Cardis et al. [10] have conducted the largest retrospective cohort study for the nuclear industry, which involved 598,068 workers (90% men) spreading around 15 countries and

Table 9.7 Potential health risk studies on waste composting

Facilities	Receptors	Exposures	Effects	Reference
Composting facilities in Germany	58 compost workers, 53 biowaste collectors and 40 control subjects	Bioaerosol: 10^7–10^6 CFU/m^3 in air	Higher recurrence of complaints relating to health and diseases	[46, 52]
41 composting facilities in Germany	66 control subjects in comparison to 218 compost workers	Respirable dust, cultivable microorganisms and endotoxins	A long period of exposure to dust (organic particle) can lead to both acute and chronic effects on the functionality of the lung and cause respiratory disorders The composting plant detected that concentrations of thermophilic actinomycetes (thermo-tolerant variations) and fungi (filamentous types) are significantly high The diagnosis of lung diseases, which is due to organic dust exposure and inhalation, seems to be related to mycotoxins	[53, 54]
Drum composting plant treating source-separated catering waste in Finland	Measurement locations for the bioaerosols were: (1) the receiving hall for biowaste, (2) the drum composting hall and (3) the control room	Bioaerosols (microbes, dust and endotoxins) Endotoxin: High 200 endotoxin units (EU) per m^3 (averaged) in 2 locations Dust: Low dust concentrations of 0.6–0.7 mg/m^3	The presence of airborne microbes and also for endotoxin is at quite a rising level for an area such as the receiving hall and the drum composting hall	[55]
2 Finnish combined-drum-and-tunnel composting plants, which is a composting sewage sludge (named Plant A) and composting source-separated biowaste (named Plant B)	–	Microbes of both mesophilic and thermophilic variations which include bacteria, fungi and actinomycetes; the total unit of microbes, the concentration level of endotoxin including noise level & dust concentration (Plant B)	Improper aerating area for Plant B seems to promote microbes' concentration built-up and also lead to endotoxin accumulation up to 200 EU/m^3 and exceeded even more in several measurements	[56]

Facilities	Receptors	Exposures	Effects	Reference
Compost plant in Germany	Workers and surrounding villages	Spores	All the collection points show a CFU of $5 \times 10^5/m^3$, which is considered high in the facility vicinity	[57]
2 composting facilities and 3 waste sorting plants in Germany	137 employees	–	The level of immunoglobulin E (IgE) in the sorting facilities increased, but no statistically significant possibility for allergic diseases risk was found The functionality of the respiratory system (lung) did not appear to have any regularity tested through spirometry There have been numerous complaints about illness such as throat sickness (38%), coughing (35%), respiratory-related sickness/infection (23%), diarrhoea (18%), muscle and joints pains (13%) and conjunctivitis (12%)	[58]
Province of Quebec, Canada	Waste collectors	Total culturable bacterial and fungal counts	Worker exposure counts were significantly ($p \leq 0.05$) which is higher than the upwind reading taken as a control measurement point Waste collection employees working with urban organic/compostable waste exhibit the highest personal exposures towards the bacteria measured in this study	[50]
Waste management chain in the Netherlands		Inhalable dust, endotoxin, $\beta(1 \rightarrow 3)$-glucan, and fungal extracellular polysaccharides	Bioaerosol exposure was lower for outdoor handling of waste, and the handling process done indoors showed potential for a much higher exposure level	[59]

(continued)

Table 9.7 (continued)

Facilities	Receptors	Exposures	Effects	Reference
Municipal waste collection and management industry in Poland	Waste collectors and composting site workers	Dust and endotoxins	The waste collection area has exhibited the most significant dust level, which is 7.7 mg/m^3 (mean value), while the composting area only showed about 4.6 mg/m^3 (mean value) in dust concentration. 4.0 mg/m^3 for total dust particles (suspended) and up to 10 ng/m^3 for endotoxin is considered as the maximum allowed concentration (MAC)	[60]
Suburban yard-waste composting facility in northern Illinois (USA)	Worker and community exposure	Bioaerosol	In the facility vicinity, the concentration of total particulate (including β(1 → 3)-glucans and endotoxin) as well as total bacteria (both the gram-negative and gram-positive bacteria) and total spores (*penicillium* and *aspergillus* spores, actinomycetes) were above than outside of the compounds. Compared to the inactive period, a much higher level of bacteria is detected when the facility is operational. Facility employee was exposed to a high level of endotoxin, β(1 → 3)-glucans and the total particulates as detected through personal samplers	[61]
US composting facilities (open and closed system)	–	Bioaerosol	The maximum value was 4356 CFU/m^3 air for actinomycetes (thermophilic), in which all the collection points within the composting facilities exhibit the presence of pathogenic species	[62]

summarised that there is hardly any extra risk of cancer developed for a cumulative radiation dose of 100 mSv. In the study, the majority of the workers, which is about 90%, were exposed to less than 50 mSv of cumulative doses while the remaining 5% received more than 100 mSv and a very small group of about 0.1% received more than 500 mSv in terms of the cumulative doses. Overall, all of these values conclude that radiation contributes to about 1–2% of deaths from cancer.

9.4.6 Overall Stages of Waste Management Processes

Table 9.8 summarises the number of studies that described various risks pertaining to waste collectors.

In the case of waste landfilling or land spreading, the most logical connection with human health effect is very likely towards congenital malformations. While for waste disposal using incineration methods, it is often related to the development or

Table 9.8 The number of studies among waste collectors evaluated in terms of a work description or the effect in terms of physical symptoms, injuries or health risk [65]

Types of health effects	# Studies increased risk? Yes/no/unclear	Recommendation/risk ratio	Strength
Work demand and health response (acute)			
Dust	4 (3/1/0)	>2.5 mg/m^3	Strong
Endotoxin	9 (8/1/0)	>50 EU/m^3	Strong
Bacteria	7 (7/0/0)	>10^4 CFU/m^3	Strong
Fungi	8 (7/1/0)	>10^4 CFU/m^3	Strong
Force on lower back due to compression	3 (2/1/0)	>3400 N	Moderate
Noise	2 (2/0/0)	>80 dB(A)	Limited
Health			
Health		Risk ratio ($P < 0.5$)	
Bronchitis or respiratory-related symptoms	7 (4/1/2)	1.9–4.1	Moderate
Nausea, diarrhoea or any other type of gastrointestinal symptoms	3 (3/0/0)	1.4–5.6	Limited
Complaints regarding upper or lower back pain (musculoskeletal)	3 (2/0/1)	2.2–2.3	Limited
Hearing impairment (loss of hearing)	2 (1/0/1)	No risk ratio	Limited
Hepatitis (A, B or C)	3 (3/0/0)	1.9 to >10	Limited
HIV	1 (1/0/0)	>10	Limited
Syphilis	1 (1/0/0)	>10	Limited
Rectal and colon cancer	1 (1/0/0)	2.5–12.5	Limited
Allergic bronchopulmonary aspergillosis	1 (1/0/0)	No risk ratio	Limited
Hantavirus	1 (0/1/0)	Not significant	Limited
Irritation of the eyes (acute)	1 (0/1/0)	Not significant	Limited
Injury			
Injuries	7 (3/0/4)	1.5–3.3	Moderate

the increase in the risk of adverse effects for sarcomas and non-Hodgkin's lymphomas. After all, dose-response study had confirmed that the primary intake pathway for dioxin is from food intake rather than from inhalation in the environment. However, very minimal discoveries were attainable on incinerators during this new generation where it is fitted with modern emission control or prevention technology, while eventually making any future epidemiological studies becoming more difficult since it became even more complex to detect excess adverse effects.

For composting activities, there are limited available findings focusing on the resident population health impact of compost, instead, there are previous studies that signify diseases related to respiratory tracts and indications of heightened antibody concentrations against actinomycetes and fungi for affected compost facility workers. There is definitely the need or urgency for more research or studies to look upon the potential pathogens pathway that could be ingested through the intake (food contamination) and environmental elements (via bioaerosol, via soil erosion or contamination through water bodies), which will subsequently affect human health especially since there is a considerable increase of soil amendments practice using manure and sewage sludge. At best, most of the available studies concentrate only on occupational diseases for the land spreading activities while activities that potentially contaminate water bodies focused on gastrointestinal symptoms and respiratory illnesses since these water bodies are used for bathing or swimming. Of all those studies, there is a significant relationship between the increased high-risk symptoms that correlate with pathogens due to contamination from sewage treatment plants. A convincing proof of dose–response relationship has been observed in most of those cases, especially with the bacterial group of enterococci and faecal streptococci. Even though there is the existing, proven data and the trend of increasing cases involving human infections in sewage-contaminated waters; there is still minimal effort done for research in this area, which is quite shocking, but again, it is mostly related to the costs involved in these kinds of viral investigations.

The more concerning waste materials are the types with high-level radioactive components generated from nuclear facilities, which are usually discarded as spent nuclear fuel. Apparently, this kind of waste is piling up in many countries, especially the developed ones, even though a decision on its final repository methods is still ongoing. The development of numerous new nuclear plants as an efficient power generator in various countries, including in the region of Asia, would likely cause the mass increase of radioactive waste to be handled. There is also the need to take into account the old nuclear power stations decommissioning, which will also be producing a low-level radioactive waste but in a considerable huge volume. It is a very delicate issue pertaining to the risk of excessive exposure to ionising radiation for the surrounding region near not only the nuclear reactors but also the nuclear-spent fuel storage facilities and its waste reprocessing facilities, whether all these facilities are still active or just at the construction stage. It would be better if the best possible technologies and controlling mechanisms are implemented even with a bit of higher cost, for the development of new reactors, as well as for the closure of old ones, and in the recycling facilities or for fuel enrichment operations as the tendency of contamination resulted from radioactive waste into the surrounding area, and likely subjection of the general public to those harmful ionising radiation could be minimised.

Even though conclusive evidence of a link was not proven by most epidemiological studies relating to the population living nearby nuclear sites and the possible adverse health effects, yet it is essentially crucial to take into account public health surveillance. This protection of general health requires new molecular monitoring techniques for exposure to ionising radiation and identification at a very early stage so that immediate remedial action can be implemented before any adverse health issues start developing. The focus on prospective cohort studies is necessary to eliminate or at the very least minimise any sort of unpredictable element in the epidemiological studies, particularly relating to much needed statistical power, consideration or inclusion of the confounding factors (including the bias for publication purpose), specifically selective biomarkers to the investigated adverse effect, and to have precise background information of the environmental exposure (various elements such as water, air, soil and food) to the contaminants, and to the operation schedule as well as the characteristic of waste management facilities.

On a global scale, industrialisation and urbanisation acceleration in developing countries along with billions of tonnes of waste produced every year will definitely require some sort of health impact studies. Moreover, the health issues associated with the disposal of waste are escalated in countries such as China and India, with unnoticed elsewhere. In order to reduce the health impact of inappropriate waste disposal methods, there is the need for the massive investment required for waste management facilities, training and education. However, the issue of health effects related to waste management also needs to be solved on other parts of waste management as well which is:

1. Implementation of preventive measures and economic gain for waste prevention, minimisation, recycling, and composting,
2. Reflect cost of the waste management costs into the end-user product,
3. Encourage public participation in better or improved waste management practices on a local, regional and even global scale,
4. Public health monitoring and surveillance, and.
5. The use of suitable biomarkers within epidemiology techniques for future or comprehensive investigations.

9.5 Practical Examples

9.5.1 Case Study: The Health and Safety of Waste Collection in Developing Countries and Developed Country

Waste management procedures in developing countries that utilise manual handling tasks are associated with numerous occupational safety and health risks such as gastrointestinal infections, respiratory and skin diseases, as well as muscular-skeletal problems and cutting injuries. Study regarding this issue done by Bleck and

Table 9.9 Occupational hazards of waste collectors [66]

Task	Hazard
Act of carrying and lifting heavy waste material while pushing heavy loads on the waste cart	Muscular-skeletal disorders
Came in contact with a dangerous item (sharp waste components) and the need to handle such items from moveable machinery parts/vehicles Not even working on an even ground such as an elevated platform (foot placement)	Mechanical hazards
Manually handle organic waste material without knowing the exact compounds or have been left for a certain period of time (contaminated with harmful substance or mould)	Biological agents
Agglomerate mixed wastes contain a mixture of materials that might react with each other and/or cause an adverse effect	Hazardous substances
Collecting electric and electronic waste from industries/commercial/workshops	Electrical risks
Collect and manually/handpick waste inside the dumpsite	Fire/explosion
Working conditions, especially on busy roads or near places with heavy machinery (workshops, construction as well as the waste collection trucks themselves)	Noise
The act of pulling/pushing vehicles or waste carts on sometimes an uneven/not properly made street/lane	Vibration
Potential criminal acts risk down the street (e.g. mugging, assaults)	Human beings
Need to get into street/private compound (e.g. guard dog/mammal); not equipped with proper protection against harmful outside elements (insects)	Animals
Negative view from the community or society since having to deal or work with garbage/waste	Psychological burden

Wettberg [66] listed out the occupational hazards of waste collectors as shown in Table 9.9.

The study was conducted in the Ethiopian capital of Addis Ababa, where woven plastic bags and one-axis pushcarts are used to transport the waste to collection points (decentral) prior to 8 m^3 containers or truck pickup. Assessments were made for collectors' working procedures, conditions and occupational safety risks, in which visual assessments were made using expert judgement while muscular-skeletal risks were classified using the Key Indicator Method for Activities Involving Lifting, Holding and Carrying [67]. Recently, a new method called The Key Indicator Method for Manual Handling Operations (KIM-MHO) was developed to assess working conditions within a cross-sectional study. Whereas ergonomic studies conducted for municipalities in Italy by Botti et al. [68] used the NIOSH Variable Lifting Index (VLI) to evaluate variable lifting tasks using the revised NIOSH lifting equation. The study concluded that there was exposure to ergonomic risk for waste collectors during the door-to-door collection of the waste, highlighting very high exposure to postural risk factors for the back-to-standing posture exhibited by the postural assessment.

9.5.2 Case Study: The Occupational Health and Safety Practices in a Micro and Small-Sized Enterprise of Portuguese Waste Management Sector

The enterprises dealing with various collection, recovery, treatment and disposal of residential as well as commercial and industrial waste are relatively small in size [68, 69], which is either micro-sized firms or small-sized firms [70]. For example, 805 enterprises in Portugal during 2014 were responsible for various waste management scopes, hiring about 14,000 employees involving about 1.5 billion (in euros) turnover [71]. The fact that these enterprises have lesser resources compared to huge companies resulted in minor priority on occupational health and safety budgeting [72]. Rodriguez et al. [73] study on the connection between OHS practices within 143 Portuguese waste management enterprises and their OHS performance. The relationship was categorised between five different OHS management practices comprised of work aspects (human, technical and organisational) and operation level (organisational and technical). Multiple hypotheses were made since OHS performance is very much affected by the legal compliant that could be summarised from H1 to H5, which is defined as:

H1—Higher legal compliance resulted in better OHS performance.
H2—More timely employer allocation to the OHS issues will result in better OHS performance.
H3—More OHS training hours will result in better OHS performance.
H4—More OHS external visitation service per year will result in a better OHS performance level.
H5—The presence of OHS policies will result in better OHS performance.

9.6 Conclusion and Summary

In many developing countries, priorities towards waste management are very poor due to the lack of resources/funds and political influence, which is also being furtherly worsened by the sub-standard education background and uncontrollable widespread of illnesses due to poor sanitation facilities that would contaminate the potable water. Even more so when the poor communities themselves are sometimes dependent upon the salvaging activities for recycling materials within the solid waste and without any proper protection would be affected not only to the physical injuries from the solid waste sorting activities but also exposed to the parasites/pathogen that could lead to an intestinal infection. Whereas in developed countries, public concern revolves more around the badly managed landfill sites and incinerators having high potential to bring negative effects on human health. This concern was aroused from the previous accident regarding industrial waste (e.g. Love Canal in the USA in the 1970s) and also major industrial accidents globally famous due to improper waste management operations, such as Seveso (Italy) in 1979 and Bhopal (India) in 1984. Other than this specific accident occurrence, there is also doubt in the general population about potential adverse effects just by being so relatively close to the modern landfills and incinerator areas. It is not convincing enough to the population as the overwhelming majority of epidemiological research has not come to any solid conclusion regarding the excess risk in catching or developing specific illnesses just by being near any type of waste management facility. This is partly caused by the environmental epidemiological research limitation and also due to enhanced technology, management and procedures of waste management activities. Therefore, thorough planned and systematic epidemiological studies are required, which would be able to gain enough evidence or data so as to measure the effect of exposure to low levels of possible harmful substances.

Overall, the existing epidemiological evidence that linked the waste management system and connected it to the impact of human health is quite controversial. This is because there is hardly any data or insufficient data on exposure directly upon humans, and most research tends to replace such information with residential data in which a recent review looked at the likely exposure pathways by measuring the pollutant level in soil or by modelling the pollution dispersion for atmospheric exposure. It is crucially important for such studies to provide data on direct human exposure which would be suitable using exposure biomarkers, feasibly acquired before and also after a waste management facility starts its active operation phase. Even more so, many of those studies have not adequately controlled the confounding factors, especially in terms of social differences/deprivation and the potential of other sources exposure compared to the one being investigated.

Glossary

Confidence interval (CI) Types of estimates computed from the statistics of the observed data

Composting Process for decomposing organic materials into simpler organic and inorganic compounds

Colony-forming unit (CFU) A unit used in microbiology to estimate the number of viable bacteria or fungal cells in a sample

Congenital anomalies A structural or functional anomaly (e.g. metabolic disorders) occurs during intrauterine life and can be identified prenatally at birth or detected later in infancy.

Decibel A or dB (A) The decibel A filter is widely used for sound measurement where the dB (A) roughly corresponds to the inverse of the 40 dB (at 1 kHz) equal-loudness curve for the human ear.

Electrostatic precipitation (ESP) A filterless device that removes fine particles, like dust and smoke, from a flowing gas using the force of an induced electrostatic charge minimally impeding the flow of gases through the unit.

Endotoxin unit (EU) Level of endotoxin since endotoxin molecular weight may vary a great deal from 10,000 to 1,000,000 Da

Epidemiology Branch of medicine deals with the incidence, distribution and control of diseases

Incinerator Furnace for the burning of waste materials

International toxic equivalent quantity (I-TEX) An approach that facilitates risk communication internationally by reducing large volumes of analytical data into an internationally recognised single number

Non-Hodgkin's lymphomas Cancer that starts in white blood cells called lymphocytes, which are part of the body's immune system

Odd risk (OR) The ratio of odds of an event in one group versus the odds of the event in the other group

Quantitative polymerase chain reaction (qPCR) A laboratory technique used by molecular biology based on a polymerase chain reaction where the amplification of a targeted deoxyribonucleic acid (DNA) molecule undergoing a chain reaction is monitored on a real-time basis.

Relative risk (RR) Risk ratio is the ratio of the probability of an outcome in an exposed group to the probability of an outcome in an unexposed group

Toxic equivalency factor (TEF) The term to express the toxicity of dioxins, furans and PCBs in terms of the most toxic form of dioxin, 2,3,7,8-TCDD

Threshold limit values (TLV) The maximum level of an airborne substance that a worker can be safely subjected to without being susceptible to harm or injury

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Chapter 10
Innovative Bioreactor Landfill and Its Leachate and Landfill Gas Management

Lawrence K. Wang and Mu-Hao Sung Wang

Abstract This publication introduces (a) the excellent leadership (XL) of the US Environmental Protection Agency (USEPA), and its newly developed bioreactor landfill technology under Project XL; and (b) the special partnership of the United Nations Industrial Development Organization (UNIDO) and the USEPA for transferring new US technologies (such as bioreactor landfill) to the developing countries and disseminating the technical information to the entire world. The entire bioreactor landfill is operated as a totally controlled engineering process reactor in which the solid waste is processed biologically, the emitted greenhouse gas (GHG) from anaerobic bioreactor landfill or hybrid bioreactor landfill is collected, treated, and reused, and the generated leachate from any type of the bioreactor landfill is recycled to the landfill for reprocessing. Not only the air pollution problem of landfill gas (LFG) and the water pollution problem of leachate are solved, but also the detention time for processing solid waste is shortened, so the landfill's useful life is almost doubled. The bioreactor landfill topics covered in this publication include (a) the three types of bioreactor landfills: aerobic bioreactor landfill, anaerobic bioreactor landfill, and hybrid bioreactor landfill; (b) biochemical theory of bioreactor landfills; (c) design and operation considerations of bioreactor landfills; (d) potential advantages of bioreactor landfills; (e) bioreactor landfill performance reports; (f) revision to the US current municipal solid waste landfill (MSWLF) rules and regulations; (g) design criteria of Project XL bioreactor landfill projects; and (h) the US regulatory overview on Project XL concerning the newly developed bioreactor landfill.

L. K. Wang (✉)
Lenox Institute of Water Technology, Latham, NY, USA

United Nations Industrial Development Organization, Vienna, Austria

M.-H. S. Wang
Lenox Institute of Water Technology, Latham, NY, USA

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Nomenclature

ANPRM	Advanced Notice of Proposed Rulemaking
CAA	Clean Air Act
$C_aH_bO_cN_dS_eP_f$	Empirical mole composition of the original organic solid wastes
CFR	Code of Federal Regulations
CH_4	Methane
CO_2	Carbon dioxide
$C_uH_vO_wN_xS_yP_z$	Empirical mole composition of the remaining organic solid wastes
CWA	Clean Water Act
eCFR	Electronic Code of Federal Regulations
FEPCA	Federal Environmental Pesticide Control Act
FML	Flexible membrane liner
GCL	Geosynthetic clay liner
GHG	Greenhouse gas
H^+	Hydrogen ion
H_2O	Water
H_2S	Hydrogen sulfide
HDPE	High-density polyethylene
IE	Industrial ecology
ISID	Inclusive and sustainable industrial development
LFG	Landfill gas
LMGOP	Landfill Methane Gas Outreach Program
MSW	Municipal solid waste
MSWLF	Municipal solid waste landfill
NARA	National Archives and Records Administration
NH_3	Ammonia
NH_4^+	Ammonium ion
NRMRL	National Risk Management Research Laboratory
O_2	Oxygen
PO_4^{3-}	Phosphate
RCRA	Resource Conservation and Recovery Act

RD & D	Research, development, and demonstration
TKN	Total Kjeldahl nitrogen
TP	Total phosphorus
UNIDO	United Nations Industrial Development Organization
USDOE	US Department of Energy
USEPA or EPA	US Environmental Protection Agency
VADEQ	Virginia Department of Environmental Quality
XL	Excellent leadership

10.1 Introduction and Summary

10.1.1 Summary

A dry tomb landfill is a traditional municipal landfill that does not intentionally add liquids to the landfill to accelerate the decomposition process of municipal solid waste (MSW). Its main goal is to keep liquids out of a traditional sanitary landfill.

A bioreactor landfill, however, is an innovative municipal solid waste landfill (MSWLF) recently developed, evaluated, and promoted by the US Environmental Protection Agency (USEPA). In a bioreactor landfill, liquids are added to help microorganisms break down the solid waste. An increase in waste degradation and stabilization is accomplished through the addition of liquid and air (if it is needed) to enhance microbial processes.

This bioreactor concept differs from the traditional 'dry tomb' municipal landfill approach because entire bioreactor landfill is operated as a totally controlled engineering process reactor in which the solid waste is processed biologically, the emitted greenhouse gas (GHG) from anaerobic bioreactor landfill or hybrid bioreactor landfill is collected, treated, and reused, and the generated leachate from any type of the bioreactor landfill is recycled to the landfill for reprocessing. Not only the air pollution problem of landfill gas (LFG) and the water pollution problem of leachate are solved, but also the detention time for processing solid waste is shortened, so the landfill's useful life is almost doubled.

The bioreactor landfill topics covered in this publication include: (a) the three types of bioreactor landfills: aerobic bioreactor landfill, anaerobic bioreactor landfill, and hybrid bioreactor landfill; (b) biochemical theory of bioreactor landfills; (c) design and operation considerations of bioreactor landfills; (d) potential advantages of bioreactor landfills; (e) bioreactor landfill performance reports; (f) revision to the US current MSWLF rules and regulations; (g) design criteria of Project XL bioreactor landfill projects; and (h) the US regulatory overview on Project XL concerning the newly developed bioreactor landfill.

10.1.2 Excellent Leadership of the US Environmental Protection Agency

US Environmental Protection Agency (USEPA) is an agency of the US government that sets and enforces national pollution-control standards. In 1970, President Richard Nixon created the USEPA to fix national guidelines and to monitor and enforce them. Functions of three federal departments (of the Interior, of Agriculture, and of Health, Education, and Welfare) and of other federal bodies were transferred to the new agency. The USEPA was initially charged with the administration of the Clean Air Act (CAA) (1970), enacted to abate air pollution primarily from industries and motor vehicles; the Federal Environmental Pesticide Control Act (FEPCA) (1972); and the Clean Water Act (CWA) (1972), regulating municipal and industrial wastewater discharges and offering grants for installing wastewater collection and treatment facilities. By the mid-1990s, the USEPA was enforcing 12 major statutes, including laws designed to control uranium mill tailings; ocean dumping; safe drinking water; insecticides, fungicides, and rodenticides; solid wastes, hazardous wastes, industrial effluent pre-treatment, and asbestos hazards in schools. The Resource Conservation and Recovery Act (RCRA) (1976) is the most important public law that creates the framework for the proper management of hazardous and non-hazardous solid waste. The RCRA law describes the solid waste management program mandated by the US Congress that gave USEPA authority to develop the RCRA program.

In addition to the responsibility of enactment and enforcement of environmental laws, regulations, and rules, USEPA has also played its excellent leadership (XL) role in (a) developing new environmental technologies, environmental training programs, technical manuals, fact sheets, guidelines, Internet information platforms, and international programs assisting the developing countries; (b) giving construction grants to the municipalities for improving their environmental infrastructure; and (c) giving research grants to the universities and institutes for continuous environmental science and engineering investigations. Under USEPA's Project XL, an innovative Bioreactor Landfill technology has been successfully developed and is now introduced by the authors in this publication for further international technical information dissemination [1–10].

10.1.3 Partnership of the United Nations Industrial Development Organization

United Nations Industrial Development Organization (UNIDO) is a specialized agency of the United Nations (UN) with about 170 member states. The member states regularly discuss and decide UNIDO's guiding principles and policies in their sessions of the policymaking organs. The UNIDO's mission is to promote a new humanity science of industrial ecology (IE) and accelerate inclusive and sustainable industrial development (ISID) in member states. Natural resource recovery, environmental sustainability, and proper management solid, liquid, and gaseous wastes are emphasized within ISID. The UNIDO's programmatic focus is structured, as detailed in the UNIDO's Medium-Term Program Framework 2018-2021, in four strategic priorities: (a) creating shared prosperity; (b) advancing economic competitiveness; (c) safeguarding the environment; and (d) strengthening knowledge and institutions. UNIDO has been a partner of USEPA for transfer of the US environmental technology to the world for many decades.

The senior author of this publication, Lawrence K. Wang, has been assigned by the US Department of the State (USDOS) to be a Senior Advisor of the United Nations Industrial Development Organization (UNIDO) and has been a USEPA Advisor/Contractor, an Advisor/Engineer of the New York State (NYS), all for humanity public service in worldwide technology transfer, developing environmental projects in developing countries, preparing environmental engineering manuals, and reviewing research/engineering grant proposals on behalf of UNIDO and USEPA. Both authors have assisted the USEPA, UNIDO, and NYS in dissemination of environmental technical information to the entire world through the US Department of Commerce, National Technical Information Service (NTIS), the United Nations Educational, Scientific and Cultural Organization (UNESCO), the Lenox Institute of Water Technology (LIWT), and international/national technical training programs and presentations [11–13, 16–23]. This publication (Bioreactor Landfill Technology) is one of many written technical information for transferring the USEPA technology to the world, especially the developing countries which have started late, thus must learn quickly from the industrial countries [11–29].

10.2 Problems of Traditional Dry Tomb Landfill

Traditional municipal landfill is a 'dry tomb landfill', which is a landfill that does not intentionally add liquids to the landfill to accelerate the decomposition process. Its main goal is to keep liquids out of a landfill. The expected lifespan of an ideal traditional municipal landfill is about 12 years although actual lifespan is much longer due to a shortage of available inexpensive land for landfilling. The overdue traditional landfill sites create many environmental problems, such as odor, landfill gas emission, polluted leachate discharge, air pollution, forest fires, and groundwater contamination.

For sustainable industrial development, an environmental engineer or an industrial ecologist always wonders whether or not a closed landfill site can be reclaimed for reuse as a golf course, park site, wildlife's sanctuary, etc. Such a land reclamation dream can finally come true when the landfill's environmental problems can be properly solved [11].

The emission landfill gas (LFG) is a major problem limiting the possibility of land reclamation after landfill closure. A typical LFG contains high concentrations of methane and odor-causing pollutants. The former (methane) is a major greenhouse gas (GHG) causing the problems of global warming and climate change; and the latter (odor-causing pollutants) creates community complaints, reduces the land value of neighbors surrounding the landfill site, and diminishes any possibility of land reclamation. One solution is collection and burning of LFG by flaring process, if the landfill is far away from a forest. Otherwise, flaring LFG could become a source of forest fires. It is known that methane is an excellent energy source. So a better sustainable industrial solution will be collection and treatment of LFG for reuse [29].

Leachate is formed when rain water filters through wastes placed in a landfill. When this liquid comes in contact with buried solid wastes in the landfill, it leaches, or draws out, chemicals or constituents from those wastes. The leachate is a main source of groundwater contamination when it goes unnoticed. When an untreated leachate is discharged to a surface water, it also pollutes surface water causing water pollution, ecological damage, and environmental violation. There have been many proposed solutions to leachate treatment, such as activated sludge, trickling, membrane bioreactor, rotating biological contactor, lagoons, chemical precipitation, chemical coagulation, clarification, granular activated carbon adsorption, filtration, ultraviolet, chemical oxidation, disinfection, etc. Although many processes have been found to be technically feasible for leachate treatment, the economically feasible solutions are still being explored.

10.3 Historical Development of Bioreactor Landfills Within the US Environmental Protection Agency

10.3.1 Joint Efforts of the US Environmental Protection Agency (USEPA) and the United Nations Industrial Development Organization (UNIDO)

Project XL (i.e., eXcellence and Leadership) is a US Environmental Protection Agency (USEPA) initiative, which began in 1995. The United Nations Industrial Development Organization (UNIDO), Vienna, Austria, has been a USEPA partner for technical information dissemination to the entire world.

The innovative Project XL program provides limited regulatory flexibility for regulated entities to conduct pilot projects in the USA that demonstrate the ability to achieve superior environmental performance. The information and lessons learned from the innovative Project XL are being used to assist USEPA in redesigning its current regulatory and policy-setting approaches. As of now, well over 51 pilot experiments have been implemented. Of those being implemented in this innovative program, four landfill pilot projects have been approved to operate as bioreactor landfills. These innovative bioreactor landfill pilot projects include the following locations: (a) Buncombe County Landfill Project, North Carolina, USA; (b) Maplewood Landfill and King George County Landfills, Virginia, USA; and (c) Yolo County Bioreactor Landfill, California, USA [1–10].

USEPA provides these municipal solid waste landfill facilities (MSWLF) with regulatory flexibility that allow them to recirculate leachate and other liquids over a MSWLF unit constructed with an alternative liner system. It is the hope of the designers of these bioreactor landfill XL projects that, when implemented, the leachate recirculation/gas recovery landfill approach would provide superior environmental performance in a number of ways such as: (a) enhanced groundwater and surface water protection; (b) reduced landfill gas (LFG) emissions and odor control by early installation and operation of LFG collection and control systems; (c) increased opportunity for LFG to be reused as a fuel; (d) added solid waste processing capacity and increased life of existing landfill cells, thereby reducing the need for new landfill sites; (e) improved leachate quality and cleaner wastewater discharges; and (f) increased opportunity for land reclamation after landfill closure.

USEPA has gained significant information on bioreactor landfill technology from these projects. All of the Project XL bioreactor landfill pilot projects are evaluated on superior environmental performance, cost savings, paperwork reduction, sustainability, innovation, feasibility, and identification of monitoring and reporting methods. The results of the bioreactor XL projects may provide information to USEPA on modifying specific criteria in the Title 40 of the Code of Federal Regulations (CFR) part 258 regulation. The Project XL pilot demonstrations are expected to be completed according to the agreed upon duration for each individual project between 2006 and 2026 [1–10].

10.3.2 Continuous Efforts of the US Environmental Protection Agency in Research, Development, and Demonstrations

The US Environmental Protection Agency (USEPA) and its state and industry partners are studying and conducting research, development, and demonstrations (RD & D) on bioreactor landfills and other landfills, such as those that re-circulate leachate. USEPA hopes to learn more about the possible effects of bioreactor operations and the costs that may be associated with them. USEPA is examining various aspects of bioreactor landfills to do the following: (a) assess the state-of-the-practice of bioreactor landfill design, operation, and maintenance; (b) identify case studies of bioreactor landfill use, especially where data exist for comparison between traditional and bioreactor approaches; (c) determine long-term monitoring needs for environmental compliance for groundwater, gas emissions, leachate quality, liner stability, physical stability, and other factors to satisfy lifecycle integrity and economic viability concerns; (d) exchange views, technical concerns and implementation concerns regarding both pending and planned regulations effecting landfills in general, and the regulatory framework to be developed for bioreactor landfills; (e) examine the economic viability, impacts and benefits of bioreactor landfill implementation at full scale; and (f) identify and prioritize research and regulatory needs.

USEPA and its partners need to collect data on the following information to make a determination regarding the benefits of bioreactor landfills, as well as to understand the concerns associated with them: (a) alternative liner design/materials for leachate recirculation and bioreactor landfills; (b) physical stability of the cover and bottom liner during and after operation of the bioreactor landfills; (c) impacts of the bioreactor landfill's leachate quality, quantity, and loading on the liner system; (d) times and amounts of liquids it takes to reach field capacity; (e) appropriate means for measuring field capacity; (f) leachate recirculation and its effect on the rate and extent of bioreactor landfill stabilization; (g) bioreactor landfill's stabilization measures; (h) design, operation, and performance specifications for bioreactor landfills; (i) bioreactor landfill's rate, quantity, and quality of gas generation; (j) interim covers used after placement to accommodate anticipated settlement; (k) daily and final cover performance; (l) optimum moisture content and distribution methods; (m) monitoring requirements of bioreactor landfills; and (o) bioreactor landfill technology impacts on capping, as well as current closure and post-closure requirements [1–10].

USEPA in collaboration with its partners has conducted many state-of-the-practice bioreactor landfill investigations. The purpose of this state-of-the-practice bioreactor landfill investigation is to compare data from bioreactor landfills with traditional dry landfills. This investigation surveys five operating bioreactor landfills and identify the regulatory, environmental, and operating parameters of these landfills. The investigation will also help to begin identifying and evaluating best operating practices and to assist USEPA in determining long-term monitoring needs for environmental compliance with groundwater standards, gas emissions, leachate quality, liner stability, physical stability, and other factors to address lifecycle integrity and economic viability concerns. The information generated from this investigation will assist owners and/or operators, as well as permit writers, to better operate and/or regulate bioreactor landfills. In addition, this investigation should lay the groundwork for USEPA to develop technical guidance and/or best practices for design, operation, and permitting the bioreactor landfill.

The National Risk Management Research Laboratory (NRMRL) of the US Environmental Protection Agency (USEPA) is also partnering with Waste Management, Inc. to conduct research on several large-scale bioreactor landfills looking at several variables. This joint research work is being conducted through a Cooperative Research and Development Agreement (CRADA). The purpose of this long-term, joint research effort is to collect sufficient information to determine the best operating practices to promote safe operation of bioreactor landfills.

10.4 Types of Bioreactor Landfills

There are three types of bioreactor landfills under development and evaluation: (a) aerobic bioreactor landfill, (b) anaerobic bioreactor landfill, and (c) hybrid aerobic-anaerobic bioreactor landfill [10].

10.4.1 Aerobic Bioreactor Landfill

An aerobic bioreactor landfill is built and operated as a totally controlled chemical and environmental engineering aerobic bioreactor. In a typical aerobic bioreactor landfill, the solid waste is packed in the landfill cells as usual but is biologically treated with added liquid and air. The landfill's leachate is removed from the bottom layer, piped to liquids storage tanks, and re-circulated into the landfill in a controlled manner. Air is injected into the waste mass using vertical or horizontal wells to promote aerobic activity and accelerate solid waste stabilization within the landfill cells. Figure 10.1 shows a cut-away view of a typical aerobic bioreactor landfill under development. The landfill leachate is removed from the bottom layer of the aerobic bioreactor landfill and piped to a liquid storage tank. From the storage tank, the leachate is piped across the top layer of landfill cell, where it is released to filter down through the landfill to be collected again. A blower forces air into the waste mass through vertical or horizontal wells located in the top layer of the landfill. Groundwater monitoring occurs at wells situated around the perimeter of the landfill.

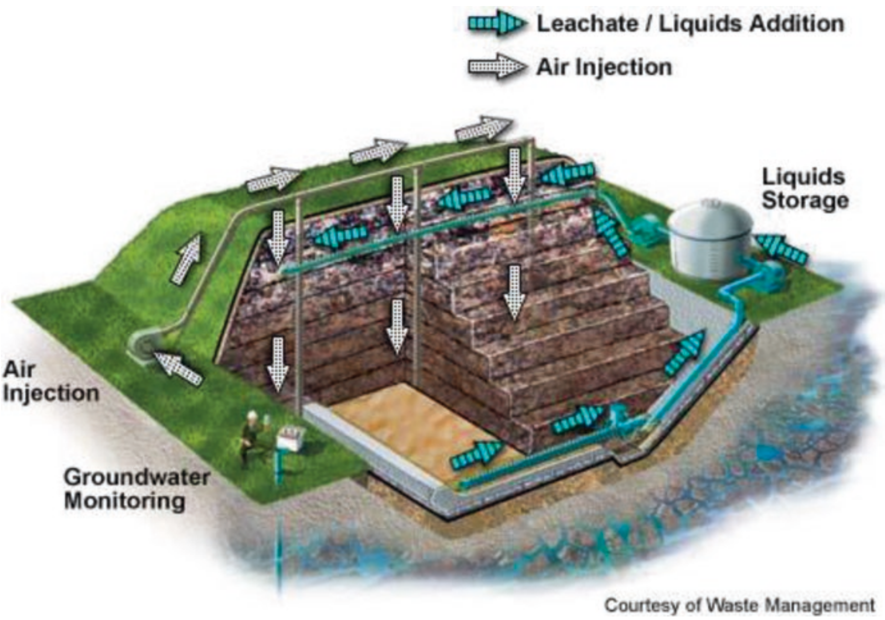

Fig. 10.1 A typical aerobic bioreactor landfill underdevelopment (Source: USEPA)

10.4.2 Anaerobic Bioreactor Landfill

An anaerobic bioreactor landfill is built and operated as a totally controlled chemical & environmental engineering anaerobic bioreactor. In a typical anaerobic bioreactor landfill, the solid waste is packed in the landfill cells as usual, but is biologically treated in the absence of oxygen. In an anaerobic bioreactor landfill, moisture is added to the waste mass in the form of re-circulated leachate and other sources to obtain optimal moisture levels. Since biodegradation occurs in the absence of oxygen (anaerobically), the landfill gas (LFG) is produced. LFG which contains primarily methane can be captured to minimize greenhouse gas (GHG) emissions and can be used for energy projects. Figure 10.2 shows a cut-away view of a typical anaerobic bioreactor with elevated levels of ammonium in the leachate. Leachate is removed via pipes from the bottom of the anaerobic bioreactor landfill and piped to an on-site biological leachate treatment facility. The facility uses facultative bacteria to nitrify the leachate ammonium to nitrate. The treated leachate and other liquids are then reinjected into the anaerobic bioreactor landfill. At the same time, landfill gas generated by the decomposing waste rises through the landfill and is collected by pipes within the waste and on top of the landfill. The landfill gas that is collected is used to generate energy. Groundwater monitoring occurs at monitoring wells situated around the perimeter of the landfill.

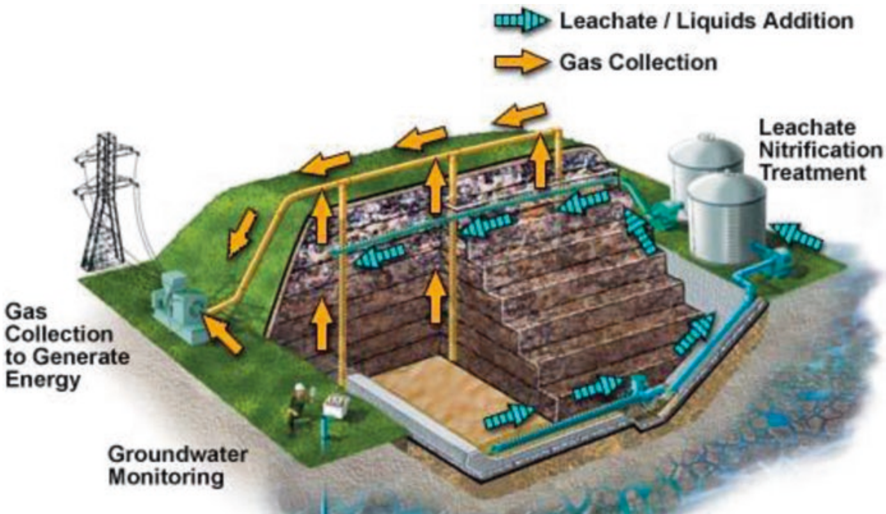

Fig. 10.2 A typical anaerobic bioreactor landfill under development (Source: USEPA)

10.4.3 Hybrid (Aerobic–Anaerobic) Bioreactor Landfill

The hybrid bioreactor landfill is a combination of the aerobic bioreactor landfill and the anaerobic bioreactor landfill which accelerates waste degradation by employing a sequential aerobic-anaerobic treatment to rapidly degrade organics in the upper aerobic sections of the landfill and collect gas from lower anaerobic sections. Operation as a hybrid results in the earlier onset of methanogenesis compared to aerobic landfills.

10.5 Biochemical Theory of Bioreactor Landfill

10.5.1 Aerobic Bioreactor Landfill

Aerobic bioreactor landfill shown in Fig. 10.1 is an aerobic biological process reactor for disposal of solid wastes. Both air and liquid are added to the bioreactor for oxidation of the solid waste in the presence of aerobic microorganisms, nutrients, and oxygen. Equation (10.1) is an over simplified biochemical reaction to represent the aerobic oxidation occurred in the bioreactor landfill for decomposition of the solid waste.

$$\mathrm{C}_a\mathrm{H}_b\mathrm{O}_c\mathrm{N}_d\mathrm{S}_e\mathrm{P}_f\left(\text{original solid waste}\right)+0.5\left(nw+2s+r-c+t\right)O_2 \tag{10.1}$$

$$\Rightarrow \begin{array}{l} n\mathrm{C}_u\mathrm{H}_v\mathrm{O}_w\mathrm{N}_x\mathrm{S}_y\mathrm{P}_z\left(\text{remaining solid waste}\right)+sCO_2+r\mathrm{H}_2\mathrm{O}+\left(d-nx\right)NH_3 \\ +\left(e-ny\right)\mathrm{SO}_4^{\,2-}+\left(f-nz\right)PO_4^{\,3-} \end{array}$$

where $r = 0.5\ [b - nv - 3(d\text{-}nx)]$; $s = a - nu$; $t = 4(e + f - ny - nz)$.

The terms $C_aH_bO_cN_dS_eP_f$, and $C_uH_vO_wN_xS_yP_z$ reflect the empirical mole composition of the organic solid wastes present at the beginning of the process and at the end, respectively [18]. The end products of an aerobic bioreactor landfill are the remaining solid waste ($C_uH_vO_wN_xS_yP_z$), carbon dioxide, water, ammonia, sulfate, and phosphate. In the presence of water, ammonia (NH_3) becomes ammonium ion ($NH_4^{\ +}$). Equation (10.1) further shows that an aerobic bioreactor landfill does not produce methane gas.

10.5.2 Anaerobic Bioreactor Landfill

Anaerobic bioreactor landfill shown in Fig. 10.2 is an anaerobic biological process reactor for the disposal of solid wastes. Only liquid is added to the anaerobic bioreactor for the decomposition of the solid waste in the presence of anaerobic microorganisms and nutrients, but in the absence of oxygen. Equation (10.2) is an over simplified biochemical reaction to represent the anaerobic process occurred in the anaerobic bioreactor landfill for decomposition of the solid waste. This anaerobic bioreactor landfill process takes much longer than the aerobic bioreactor landfill process. The resulting final products usually consist of CH_4, CO_2, NH_3, hydrogen sulfide, and acid. Hydrogen sulfide is one of odor-causing substances and produces a foul odor. Under anaerobic conditions, the decomposing substances tend to be more acidic.

$$C_aH_bO_cN_dS_e\,(\text{original solid waste}) \tag{10.2}$$

$$\Rightarrow \begin{array}{l} nC_uH_vO_wN_xS_y\,(\text{remaining solid waste}) + mCH_4 + sCO_2 + rH_2O + (d - nx)NH_3 \\ + tH_2S + (-4nu - nv + 2nw + 3nx + 2ny + 4a + b - 2c - 3d - 2e - 8m)H^+ \end{array}$$

where $s = a - nu - m$; $r = c - nw - 2\,s$, and $t = e - ny$.

10.5.3 Hybrid (Aerobic–Anaerobic) Bioreactor Landfill

Equations (10.1) and (10.2) show the biochemical reactions of aerobic portion and anaerobic portion, respectively, of a hybrid (aerobic–anaerobic) bioreactor landfill.

10.6 Design and Operation Considerations of Bioreactor Landfills

10.6.1 Leachate and Liquid Management

The bioreactor accelerates the decomposition and stabilization of waste. At a minimum, leachate is injected into the bioreactor to stimulate the natural biodegradation process. Bioreactors often need other liquids such as storm water, wastewater, and wastewater treatment plant sludge to supplement leachate. This enhances the microbiological process by purposeful control of the moisture content and differs from a landfill that simply recirculates leachate for liquids management. Landfills that simply recirculate leachate may not necessarily operate as optimized bioreactors.

Moisture content is the single most important factor that promotes the accelerated decomposition. The bioreactor technology relies on maintaining optimal moisture content near field capacity—approximately 35–65%—and adds liquids when it is necessary to maintain that percentage. The moisture content, combined with the biological action of naturally occurring microbes, decomposes the waste. The microbes can be either aerobic or anaerobic.

Due to degradation of organics and the sequestration of inorganics, research has shown that municipal solid waste can be rapidly degraded and made less hazardous by optimizing and controlling the moisture within the landfill under aerobic and/or anaerobic conditions. Leachate quality in a bioreactor rapidly improves, which leads to reduced leachate disposal costs. Landfill volume may also decrease with the recovered airspace offering landfill operators the full operating life of the landfill [1–10].

10.6.2 Landfill Gas Management

An aerobic bioreactor landfill does not generate methane gas (Eq. 10.1). A side effect of an anaerobic bioreactor landfill or a hybrid aerobic–anaerobic bioreactor landfill is that it produces landfill gas (LFG) like methane (Eq. 10.2) in its anaerobic unit at an earlier stage in the landfill's life at an overall much higher rate of generation than traditional landfills.

The Landfill Methane Gas Outreach Program (LMOP) is a voluntary program that works cooperatively with industry stakeholders and waste officials to reduce or avoid methane emissions from landfills. LMOP encourages the recovery and beneficial use of biogas generated from organic municipal solid waste (MSW) [30].

LFG emitted by an aerobic bioreactor landfill or a hybrid aerobic–anaerobic bioreactor landfill consists primarily of methane and carbon dioxide (Eq. 10.2), as well as lesser amounts of volatile organic chemicals and/or hazardous air pollutants.

Research indicates that the operation of a bioreactor landfill may generate LFG earlier in the process and at a higher rate than the traditional landfill. The bioreactor landfill LFG is also generated over a shorter period of time, because the LFG emissions decline as the accelerated decomposition process depletes the source waste faster than in a traditional landfill. The net result appears to be that the bioreactor produces more LFG overall than the traditional landfill does.

The bioreactor landfill increases the feasibility for cost-effective LFG recovery, which could reduce fugitive emissions. This presents an opportunity for beneficial reuse of bioreactor landfill LFG in energy recovery projects. The use of LFG in traditional and bioreactor landfills for energy applications is currently only about 10% of its potential use. The US Department of Energy (USDOE) estimates that if the controlled bioreactor landfill technology was applied to 50% of the waste currently being landfilled, it could provide over 270 billion cubic feet of methane a year. This is equivalent to 1% of the United States electrical needs.

10.6.3 Special Considerations for Bioreactor Landfills

Several considerations about bioreactor landfills must be examined and understood before USEPA and the State environmental agency can approve specific bioreactor standards or an environmental project engineer can recommend specific operating parameters.

Bioreactor landfills generally are engineered systems that have higher initial capital costs and require additional monitoring and control during their operating life, but are expected to involve less monitoring over the duration of the post-closure period than conventional "dry tomb" landfills. Issues that need to be addressed during both design and operation of a bioreactor landfill include the following: (a) increased gas emissions; (b) increased odors; (c) physical instability of waste mass due to increased moisture and density; (d) instability of liner systems; (e) surface seeps; and (f) landfill fires. Apparently more research, development, and demonstration (RD & D) for bioreactor landfills will be needed.

10.6.4 Specific Design Criteria and Monitoring Specifications of Project XL Bioreactor Landfill Projects

The Project XL (i.e. excellence and leadership) was initiated by the US Environmental Protection Agency (USEPA) in 1995 and is still an on-going project because the research, development, and demonstration (RD & D) of this innovative bioreactor landfill is a long-term engineering research project. The researchers and practicing environmental engineers around the world are encouraged to follow the footsteps of the USEPA for further testing or direct construction of bioreactor landfills. Important detailed design criteria and monitoring specifications of three bioreactor landfills are fully documented in the following three Appendixes for the convenience of the readers:

Appendix 1: § 258.41 Project XL Bioreactor Landfill Projects: Buncombe County, North Carolina Project XL Bioreactor Landfill Requirements
Appendix 2: § 258.41 Project XL Bioreactor Landfill Projects: Module D of the Yolo County Central Landfill Requirements
Appendix 3: § 258.41 Project XL Bioreactor Landfill Projects: Virginia Landfills XL Project Requirements.

The above technical information (CFR Title 40, updated as of September 30, 2021) is from the US Code of Federal Regulations (CFR) which is the official legal print publication containing the codification of the general and permanent rules published in the Federal Register by the departments and agencies of the Federal Government. The Electronic Code of Federal Regulations (eCFR) is a continuously updated online version of the CFR. It is not an official legal edition of the CFR.

10.7 Potential Advantages of Bioreactor Landfills

Decomposition and biological stabilization of the waste in a bioreactor landfill can occur in a much shorter time than in a traditional "dry tomb" municipal sanitary landfill. This can provide a potential decrease in long-term environmental risks and landfill operating and post-closure costs. Potential advantages of bioreactors include the following: (a) decomposition and biological stabilization in years versus decades in "dry tombs" municipal sanitary landfill; (b) at least double the useful years of landfill; (c) lower waste toxicity and mobility due to both aerobic and anaerobic conditions of bioreactor landfills; (d) reduced leachate disposal costs; (e) a 15–30% gain in landfill space due to an increase in density of waste mass; (f) elimination of groundwater and surface water contamination; (g) elimination of odor pollution (H_2S) if LFG is captured; (h) elimination of major greenhouse gas (methane) pollution, if LFG is captured; (i) significant increased LFG generation that, when captured, can be used for energy use onsite or sold; (j) reduced post-closure care; and (k) increased opportunity of land reclamation after bioreactor landfill closure.

10.8 Bioreactor Landfill Performance Reports

USEPA's research and demonstration studies for bioreactor landfills showed that a landfill using leachate recirculation can be designed and operated to increase the rate of waste stabilization. This process significantly increases the rate of biodegradation of the waste (similar to anaerobic composting), thereby reducing the waste stabilization period from 5 to 10 years (instead of 30 or more years) for a conventional "dry tomb" designed facility. So far, the USEPA has studied five bioreactor sites and investigated their performance. The following lists the specific parameters studied: (a) leachate head on liner, (b) side slope stability, (c) settlement, (d) leachate collection, (e) gas collection, and (f) prevention of fires. The purpose of this report is to evaluate specific parameters affecting bioreactor performance, including (1) leachate head on a liner, (2) settlement, (3) side slope stability, (4) fire prevention, and (5) gas collection. Previous sections evaluated each of these parameters related to protecting human health and the environment at the five sites described therein. Key findings are presented below.

10.8.1 Liner Head Maintenance

The landfill that has measured the highest leachate recirculation rate (loading rate) was Crow Wing County. About 75 gallons of leachate per ton of MSW were recirculated in 2005. There have been no problems noted in maintaining less than or equal to 30 cm of head of leachate on the primary liner. CWCL also is the only landfill of the five evaluated that has lysimeters (leak detection system) below the primary liner and leachate sump. The flow in the leak detection system is below levels of concern and has not correlated with the rates of leachate recirculation or leachate generation and/or rainfall over the history of the landfill.

The other four bioreactor landfills had no historical problems in maintaining less than 30 cm of head of leachate on the liner. Williamson County Landfill and New River Regional Landfill reported historically low leachate head (10 cm or less) during the bioreactor operations. NRRL also is the only bioreactor of the five evaluated that was able to maintain low heads with a "pipe-less" collection system design using only triplanar geocomposite for the drainage media with gravity flow to a collection sump. There also was no apparent correlation of leachate recirculation rates, leachate generation rates, and liner head maintenance in any of the five bioreactors reviewed. This most likely is due to good moisture distribution of the leachate recirculation system designs and operations that evenly dispersed leachate laterally and vertically into the waste mass to the point of absorption (i.e., less than field capacity).

As was demonstrated at each site, with each having a different leachate collection approach, the engineered systems are all functioning as intended to maintain head less than 1 ft over the liner.

10.8.2 Settlement

A common variable between all five of the bioreactor landfills has been the use and recommendation of HDPE pipe (solid and perforated) that is flexible enough to handle settlement. Experience at Williamson County Landfill bioreactor has shown that the type of piping material selected is important to the delivery of air and fluids. At first, PVC header pipe and joint connections were used. This was found to be brittle after exposure to sun and also was subject to settlement and cracking. As a result, air leaks were found (which was important since this was an aerobic bioreactor). After piping was replaced with HDPE, there have been no problems with integrity even with additional settlement of the landfill.

Only Burlington County Landfill bioreactor reported initial problems with infrastructure and settlement. They observed that the lateral injection and gas collection system piping were pulled inward to the landfill slope with settlement, causing the header pipe connection to crimp or kink. This problem later was corrected by replacement of new pipe with adequate "slack" within it, especially at connection of header and lateral piping.

The NRRL also allowed for settlement in their design and installation and did not observe any structural damage to infrastructure. Salem County Landfill bioreactor also used and recommended HDPE pipe with extra slack to allow for settlement and has not noted any infrastructure problems due to settlement. Crow Wing County Landfill bioreactor used a unique design of 4″ pipe placed in an overlapping 5″ pipe with a Furnco coupling. This allowed sufficient flexibility in the joint and slack for settlement. No problems with leachate injection systems have been observed since the leachate recirculation started in 1998.

10.8.3 Sideslope Stability

The only landfill that witnessed side slope issues was Williamson County aerobic bioreactor. This facility had two minor veneer failures, most likely due to its steep side slope of 1.5:1. The first failure was in a small area and was only the compost cover slumping due to heavy rainfall and run-off. There was no failure noted in the waste mass within the landfill or due to bioreactor operations. The second failure was due to excess pressure noted in one well which may have been created by air and leachate injection. Leachate seeps midway up the slope appeared to have been the cause of this veneer slumpage. When the cover was replaced, there were no further incidents as leachate and air quantities were lowered for injection back into this section of the landfill.

Burlington County Landfill had leachate seeps most likely due to gas wells that were watered out and leachate recirculation lines that were perforated within 7.6 m (25 ft) of the side slope. This was corrected and has never occurred since then as gas wells were equipped with dewatering pumps and leachate recirculation was terminated in this section of the landfill. None of the other landfills had side slope issues or instability.

It appears that bioreactors that design and operate with the prevention of potential leachate seeps in side slopes do not experience slope instability. A functioning leachate injection line from 15 to 30 m (50–100 ft) from the edge of the outside slope should ensure that pore pressures will not build up to affect slopes. Also, the use of alternate and permeable daily cover will help avoid seeps and instability.

10.8.4 Fire Prevention

Two of the five landfills reported experiencing conditions which posed the potential for "fires." Williamson County Landfill bioreactor had a "hot spot" over their temperature goal which was quickly remedied by adding more leachate and reducing air injection. No hot spots occurred again as monitoring and liquid management controlled temperatures.

Burlington County Landfill bioreactor had a "hot spot" that appeared to be a subsurface fire, but was readily controlled by reducing vacuum on the gas wells and balancing the system. The condition was caused by too much air withdrawn through the thin interim permeable cover. It was controlled by the addition of extra leachate injected in the area.

It appears that fire prevention and occurrence is similar in frequency to "dry tomb" landfills and is a matter of gas tuning, balancing, and monitoring. Excessive air intrusion and dryness of MSW contribute to fires in any landfill. Aerobic bioreactor landfills may be most vulnerable, but it is a matter of monitoring and control of liquid addition. NRRL also found that in aerobic landfills the simultaneous addition of liquids and reduction in air injection volume will help control temperatures in a desirable operating range.

10.8.5 Gas Collection

There were no gas collection systems necessary for the non-aerobic landfills that included Williamson County Landfill and the aerobic portion of NRRL. Methane that existed in both of these "retro-fit" landfills was oxidized within a day or two of operation and did not pose a threat to the environment as there were no gas migration issues. Also, due to its size, Crow Wing County Landfill did not install active gas systems as it is passively vented. Plans are to install an active system within the next year and sell landfill gas for energy.

The other anaerobic bioreactors that had installed gas collection systems designed and installed them during construction of the leachate injection systems. Both horizontal and vertical gas collection systems were installed and operated. A common theme was to install dewatering pumps and also to locate gas extraction systems well away from active leachate injection systems. Also, some landfills did not operate gas collection in areas of active leachate injection. Most sites also rotated the injection of leachate around the site so as to not over saturate any one area and to allow time for leachate to drain. This should also provide relief to gas collection systems.

Burlington County Landfill bioreactor also discovered that if vertical gas wells are installed deep within the zone of active biodegradation, then the temperatures in the waste are such that PVC pipe will weaken. There were a few vertical gas wells that were "crimped" at depth. They will be replaced with CPVC that has a higher melting (or weakening) point.

10.8.6 Brief Summary of the Bioreactor Landfill Performance Study

A review of the literature and evaluation of five selected full-scale operating bioreactor landfills shows the following [1]:

1. The types of bioreactor landfills studied can comply with the existing Part 258 solid waste regulations and technical guidance.
2. The addition of leachate and other liquids can be managed with appropriate design and operation of injection systems that evenly distribute the moisture within the waste.
3. The design of leachate collection systems appears to be adequate to handle any additional leachate generated as all sites have been able to maintain leachate levels under 30 cm of head on the liner.
4. Slope stability issues have been minor and are readily corrected. Proper design and operations can also provide for slope stability.
5. Fires or "hot spots" appear to have greater potential in aerobic landfills but can be managed with good monitoring and prompt addition of liquids. The anaerobic bioreactors have similar issues as a normal landfill-balancing, tuning, and monitoring of the gas extraction systems.

Additional bioreactor projects and information on bioreactor landfills and bioreactor landfill projects can be found from the USEPA publications [1–10] as well as the following sources:

1. Aerobic Landfill Technology aerobic landfill technology provided by Environmental Control Systems, Inc.
2. Yolo County Landfill provides information which is piloting a bioreactor (wet cell) landfill operation, which increases the rate of waste decomposition and increases the rate of methane production for more efficient methane collection and use.

10.9 Revision of the United States Current Municipal Solid Waste Landfill Rules and Regulations

10.9.1 Revision to the Research, Development, and Demonstration (RD & D) Permits Rule for Municipal Solid Waste Landfills

On May 10, 2016, a final rule was published in the *Federal Register* revising the maximum permit term for Municipal Solid Waste Landfill (MSWLF) units operating under RD & D permits. This final rule allows the Research, Development, and Demonstration (RD & D) permits for municipal solid waste landfill bioreactors to be extended from 12 to up to 21 years. The rule allows Directors of USEPA approved state waste programs to increase the number of renewals for such permits from three to six.

10.9.2 Revisions to Address Liquids Management in Landfills

USEPA is considering proposing changes to the current municipal solid waste landfill (MSWLF) regulations or possibly developing a separate set of regulations specific to wet and bioreactor landfills. There is an Advanced Notice of Proposed Rulemaking (ANPRM). The purpose of this ANPRM was to solicit data and information. Below is key information from ANPRM: (a) The premise of the ANPRM is that adding liquids to landfills may have benefits in contrast to dry tomb landfills; (b) USEPA data research suggests that adding liquids to MSWLFs may reduce environmental risks and increase economic benefits, provided that landfill gas (LFG) collection and leachate containment systems are in place; (c) Environmental risk may be reduced through faster waste subsidence and stabilization, decreased need for transport and treatment of leachate, and a shorter time for post-closure care; (d) Economic benefits may result from the accelerated generation of LFG for use as a renewable fuel, and reduced costs for leachate treatment and post-closure care.

10.9.3 Regulatory Overview on Project XL Concerning Bioreactor Landfills

An important regulatory overview on Project XL can be found in Appendix 4, United States Regulatory Overview on Project XL Concerning the Newly Developed Bioreactor Landfills.

Glossary

Aerobic bioreactor landfill It is built and operated as a totally controlled chemical and environmental engineering aerobic bioreactor. In a typical aerobic bioreactor landfill, the solid waste is packed in the landfill cells as usual but is biologically treated with added liquid and air. The landfill's leachate is removed from the bottom layer, piped to liquid storage tanks, and re-circulated into the landfill in a controlled manner. Air is injected into the waste mass using vertical or horizontal wells to promote aerobic activity and accelerate solid waste stabilization within the landfill cells.

Anaerobic bioreactor landfill An anaerobic bioreactor landfill is built and operated as a totally controlled chemical and environmental engineering anaerobic bioreactor. In a typical anaerobic bioreactor landfill, the solid waste is packed in the landfill cells as usual, but is biologically treated in the absence of oxygen. In an anaerobic bioreactor landfill, moisture is added to the waste mass in the form of re-circulated leachate and other sources to obtain optimal moisture levels. Since biodegradation occurs in the absence of oxygen (anaerobically), the landfill gas (LFG) is produced. LFG which contains primarily methane can be captured to minimize greenhouse gas (GHG) emissions and can be used for energy projects.

Bioreactor landfill It is an innovative municipal solid waste landfill (MSWLF) recently developed, evaluated, and promoted by the US Environmental Protection Agency (USEPA). In a bioreactor landfill, liquids are added to help microorganisms break down the solid waste. An increase in waste degradation and stabilization is accomplished through the addition of liquid and air to enhance microbial processes. Entire bioreactor is operated as a totally controlled process reactor in which the solid waste is processed biologically, the emitted gas is collected, treated and reused, and the generated leachate is recycled to the bioreactor for reprocessing. Not only the air pollution problem of landfill gas (LFG) and the water pollution of leachate are under control, but also the solid waste is processed in a much shorter detention time, so the landfill's operating life is almost doubled.

Dry tomb landfill A dry tomb landfill is a traditional municipal landfill that does not intentionally add liquids to the landfill to accelerate the decomposition process of municipal solid waste (MSW). Its main goal is to keep liquids out of a traditional sanitary landfill.

Hybrid bioreactor landfill The hybrid bioreactor landfill is a combination of the aerobic bioreactor landfill and the anaerobic bioreactor landfill which accelerates waste degradation by employing a sequential aerobic–anaerobic treatment to rapidly degrade organics in the upper aerobic sections of the landfill and collect gas from lower anaerobic sections. Operation as a hybrid results in the earlier onset of methanogenesis compared to aerobic landfills.

United Nations Industrial Development Organization (UNIDO) It is a specialized agency of the United Nations (UN) with about 170 member states. The member states regularly discuss and decide UNIDO's guiding principles and policies in their sessions of the policymaking organs. The UNIDO's mission is to promote a new humanity science of industrial ecology (IE) and accelerate inclusive and sustainable industrial development (ISID) in member states. Natural resources recovery, environmental sustainability, and proper management solid, liquid, and gaseous wastes are emphasized within ISID. The UNIDO's programmatic focus is structured, as detailed in the UNIDO's Medium-Term Program Framework 2018-2021, in four strategic priorities: (a) creating shared prosperity, (b) advancing economic competitiveness, (c) safeguarding the environment, and (d) strengthening knowledge and institutions. Since UNIDO is mainly assisting developing countries, so some industrialized countries which are the UN member states have refused to pay the UNIDO membership fees becoming the UNIDO member states.

US Environmental Protection Agency (USEPA) It is an agency of the US government that sets and enforces national pollution-control standards. In 1970, President Richard Nixon created the USEPA to fix national guidelines and to monitor and enforce them. Functions of three federal departments (of the interior, of agriculture, and of health, education, and welfare) and of other federal bodies were transferred to the new agency. The USEPA was initially charged with the administration of the Clean Air Act (CAA) (1970), enacted to abate air pollution primarily from industries and motor vehicles; the Federal Environmental Pesticide Control Act (FEPCA) (1972); and the Clean Water Act (CWA) (1972), regulating municipal and industrial wastewater discharges and offering grants for installing wastewater collection and treatment facilities. By the mid-1990s, the USEPA was enforcing 12 major statutes, including laws designed to control uranium mill tailings; ocean dumping; safe drinking water; insecticides, fungicides, and rodenticides; solid wastes, hazardous wastes, industrial effluent pretreatment, and asbestos hazards in schools. The Resource Conservation and Recovery Act (RCRA) (1976) is the most important public law that creates the framework for the proper management of hazardous and non-hazardous solid waste. The RCRA law describes the solid waste management program mandated by the US Congress that gave USEPA authority to develop the RCRA program. In addition to the responsibility of enactment and enforcement of environmental laws, regulations, and rules, USEPA has also played its excellent leadership (XL) role in (a) developing new environmental technologies, environmental training programs, technical manuals, fact sheets, guidelines, Internet information platforms, and international programs assisting the developing countries; (b) giving construction grants to the municipalities for improving their environmental infrastructure; and (c) giving research grants to the universities and institutes for continuous environmental science and engineering investigations.

Appendix 1: § 258.41 Project XL Bioreactor Landfill Projects: Buncombe County, North Carolina Project XL Bioreactor Landfill Requirements

(a) Buncombe County, North Carolina Project XL Bioreactor Landfill Requirements. Paragraph (a) of this section applies to Cells 1, 2, 3, 4, and 5 of the Buncombe County Solid Waste Management Facility located in the County of Buncombe, North Carolina, owned and operated by the Buncombe County Solid Waste Authority, or its successors. This paragraph (a) will also apply to Cells 6, 7, 8, 9, and 10, provided that the EPA Regional Administrator for Region 4 and the State Director determine that the pilot project in Cells 3, 4, and 5 is performing as expected and that the pilot project has not exhibited detrimental environmental results.

1. The Buncombe County Solid Waste Authority is allowed to place liquid waste in the Buncombe County Solid Waste Management Facility, provided that the provisions of paragraphs (a)(2) through (9) of this section are met.
2. The only liquid waste allowed under this section is leachate or gas condensate derived from the MSWLF, which may be supplemented with water from the French Broad River. The owner or operator shall control any liquids to the landfill to assure that the average moisture content of the landfill does not exceed 50% by weight. Liquid addition and recirculation is allowed only to the extent that the integrity of the landfill including its liner system is maintained, as determined by the State Director.
3. The MSWLF unit shall be designed and constructed with a liner and leachate collection system as described in § 258.40(a)(2) or paragraphs (a)(4) and (5) of this section. The owner or operator must place documentation of the landfill design in the operating record and notify the State Director that it has been placed in operating record;
4. Cells 3–10 shall be constructed with a liner system consisting of the components described in paragraphs (a)(4)(i) through (v) of this section, or an equivalent or superior liner system as determined by the State Director:

    (i) A lower component consisting of at least 18 in. of compacted soil with a hydraulic conductivity of no more than 1×10^{-5} cm/s.
    (ii) An upper component consisting of a minimum 30-millimeter (“mil”) flexible membrane liner (FML) or 60-mil if High Density Polyethylene (“HDPE”) is used.

(iii) A geosynthetic clay liner (GCL) overlaying and in direct contact with the 18 in. of compacted soil in paragraph (a)(4) of this section and having the following properties: (A) The GCL shall be formulated and manufactured from polypropylene geotextiles and high swelling containment resistant sodium bentonite. The bentonite-geotextile liner shall be manufactured using a minimum of one pound per square foot as determined using the Standard Test Method for Measuring Mass per Unit Area of Geotextiles, ASTM D-5261-92 (reapproved in 1996). The high swelling sodium montmorillonite clay shall be at 12% moisture content as determined by the Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass, ASTM D2216-98. The Director of the Federal Register approves this incorporation by reference with 5 U.S.C. 552(a) and 1 CFR part 51. These methods are available from The American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959. These methods may be inspected at EPA's docket office located at Crystal Gateway, 1235 Jefferson Davis Highway, First Floor, Arlington, Virginia, or at the National Archives and Records Administration (NARA); (B) The encapsulating geotextile shall be polypropylene and shall have a minimum weight of 6 oz./square yard.

(iv) The upper component shall be installed in direct and uniform contact with an overlaying soil cushioning component.

(v) Underlying the above liner system, there shall also be installed a leak detection system consisting of a 60-mil HDPE liner placed on a prepared subgrade: (A) A 4 inch capped pipe will drain liquid collected in the sump out beyond the footprint of the landfill cell; (B) Water collected on the leak detection liner shall be monitored at least semi-annually as directed by the State Director to determine whether any leachate escaped the liner system.

5. Cells 3–10 shall be designed and constructed with a leachate collection system to maintain less than 30 centimeters depth of leachate is present at the sump location. The leachate collection system shall include a continuous monitoring system to monitor depth of leachate.
6. The owner/operator shall keep the Federally Enforceable State Operating Permit (FESOP) issued by the Western North Carolina Air Quality Agency for the Buncombe County Solid Waste Management Facility in effect and shall comply with the provisions of the FESOP, during the entire period of leachate recirculation and the post closure period. The FESOP was issued on November 13, 2000, and contains the air quality requirements for the Buncombe County Landfill XL project.
7. Monitoring and reporting requirements. The owner or operator of the Buncombe County Solid Waste Management Facility shall monitor for the parameters listed in paragraphs (a)(7)(i) through (xiii) of this section and submit an annual report on the XL project to the USEPA Regional Administrator for Region 4 and the State Director. The first report is due coincident with the October 2001 report to

the state. The report should state what progress has been made toward the superior environmental performance and other commitments as stated in the Final Project Agreement. The report shall include, at a minimum, the following data:

(i) Amount of landfill gas generated.
(ii) Percent capture of landfill gas, if known.
(iii) Quality of the landfill gas, amount and type of liquids applied to the landfill.
(iv) Method of liquids application to the landfill.
(v) Quantity of waste placed in the landfill.
(vi) Quantity and quality of leachate collected.
(vii) Quantity of leachate recirculated back into the landfill.
(viii) Information on the pretreatment of waste applied to the landfill.
(ix) Data collected on landfill temperature and moisture content.
(x) Data on the leachate pressure (head) on the liner.
(xi) Observations, information, and studies made on the physical stability of the MSWLF units that are developed during the project term, if any.
(xii) The above data may be summarized, and, at a minimum shall contain, the minimum, maximum, median, and average data points as well as the frequency of monitoring as applicable.
(xiii) The method and frequency of monitoring shall be specified by the State Director.

8. Termination and withdrawal.

   (i) Paragraph (a) of this section will terminate August 22, 2026, unless a subsequent rulemaking is issued or terminated earlier pursuant to paragraph (a)(8)(ii) of this section.
   (ii) In the event of noncompliance with paragraph (a) of this section, USEPA may terminate the authority under paragraph (a) of this section and the authority to add liquid wastes to all or part of cells 3–10 under § 258.28(a)(3). The USEPA Regional Administrator will provide written notice of intent to terminate to the Buncombe County Solid Waste Authority with a copy to the State Director. The notice will state EPA's intent to terminate under the rules and will include a brief statement of EPA's reasons for its action. The termination will take effect 60 days from the date of the notice, unless the EPA Regional Administrator for Region 4 issues a written notice rescinding the termination.

9. Compliance requirements in the event of termination or withdrawal. The Buncombe County Solid Waste Management Facility will be subject to all regulatory provisions applicable to MSWLFs upon termination of authority under this section. In the event of early termination of this section, the EPA Regional Administrator for Region 4 may provide an interim period of compliance to allow Buncombe County a reasonable period of time for transition following cessation of liquid addition.

Appendix 2: § 258.41 Project XL Bioreactor Landfill Projects: Module D of the Yolo County Central Landfill Requirements

Paragraph (b) of this section applies solely to Module D of the Yolo County Central Landfill owned and operated by the County of Yolo, California, or its successors. It allows the Yolo County Central Landfill to add bulk or noncontainerized liquid wastes to Module D under the following conditions:

1. Module D shall be designed and constructed with a composite liner as defined in § 258.40(b) and a leachate collection system that functions and continuously monitors to ensure that less than 30 centimeters depth of leachate is maintained over the liner.
2. The owner or operator of the Yolo County Central Landfill must ensure that the concentration values listed in Table 1 of § 258.40 are not exceeded in the uppermost aquifer at the relevant point of compliance for the landfill as specified by the State Director under § 258.40(d).
3. The owner or operator of the Yolo County Central Landfill shall demonstrate that the addition of any liquids to Module D does not result in an increased leakage rate and does not result in liner slippage, or otherwise compromise the integrity of the landfill and its liner system, as determined by the State Director.
4. The owner or operator of the Yolo County Central Landfill must ensure that Module D is operated in such a manner so as to prevent any landfill fires from occurring.
5. The owner or operator of the Yolo County Central Landfill shall submit an annual report to the USEPA Regional Administrator and the State Director. The first report is due within 18 months after August 13, 2001. The report shall state what progress the Project is making toward the superior environmental performance as stated in the Final Project Agreement. The data in paragraphs (b)(5)(i) through (xvi) of this section may be summarized, but, at a minimum, shall contain the minimum, maximum, median, and average data points as well as the frequency of monitoring, as applicable. These reporting provisions shall remain in effect for as long as the owner or operator of the Yolo County Central Landfill continues to add liquid waste to Module D. Additional monitoring, record keeping and reporting requirements related to landfill gas will be contained in a permit executed by the local air quality management district pursuant to the Clean Air Act, 42 U.S.C. 7401 *et seq.* Application of this site-specific rule to the Yolo County Central Landfill is conditioned upon the issuance of such permit. The annual report will include, at a minimum, the following data:

   (i) Amount of landfill gas generated.
   (ii) Percent capture of landfill gas.
   (iii) Quality of the landfill gas.
   (iv) Amount and type of liquids applied to the landfill.
   (v) Method of liquid application to the landfill.

(vi) Quantity of waste placed in the landfill.

(vii) Quantity and quality of leachate collected, including at least the following parameters, monitored, at a minimum, on an annual basis: (A) pH; (B) conductivity; (C) dissolved oxygen; (D) dissolved solids; (E) biochemical oxygen demand; (F) chemical oxygen demand; (G) organic carbon; (H) nutrients (including ammonia [“NH_3”], total Kjeldahl nitrogen [“TKN”], and total phosphorus [“TP”]); (I) common ions; (J) heavy metals; (K) organic priority pollutants; and (L) flow rate.

(viii) Quantity of leachate recirculated back into the landfill.

(ix) Information on the pretreatment of solid and liquid waste applied to the landfill.

(x) Landfill temperature.

(xi) Landfill moisture content.

(xii) Data on the leachate pressure (head) on the liner.

(xiii) The amount of aeration of the waste.

(xiv) Data on landfill settlement.

(xv) Any information on the performance of the landfill cover.

(xvi) Observations, information, or studies made on the physical stability of the landfill.

6. This section will remain in effect until August 13, 2006. By August 13, 2006, Yolo County Central Landfill shall return to compliance with the regulatory requirements which would have been in effect absent the flexibility provided through this Project XL site-specific rule. This section applies to Phase I of Module D. This section will also apply to any phase of Module D beyond Phase I only if a second Final Project Agreement that describes the additional phase has been signed by representatives of USEPA Region 9, Yolo County, and the State of California. Phase I of Module D is defined as the operation of 12 acres of the 20 acre Module D.

Appendix 3: § 258.41 Project XL Bioreactor Landfill Projects: Virginia Landfills XL Project Requirements

(c) Virginia Landfill XL Project Requirements. Paragraph (c) of this section applies solely to two Virginia landfills operated by the Waste Management, Inc. or its successors: The Maplewood Recycling and Waste Disposal Facility, located in Amelia County, Virginia (“Maplewood Landfill”); and the King George County Landfill and Recycling Facility, located in King George County, Virginia (“King George Landfill”) collectively hereinafter, “the VA Project XL Landfills or landfill.” The VA Project XL Landfills are allowed to add non-hazardous bulk or non-containerized liquids including leachate, storm water and truck wash water, hereinafter, “liquid or liquids,” to Cell 3 of the King George Landfill (hereinafter

"Cell 3") and Phases 1 and 2 of the Maplewood Landfill (hereinafter "Phases 1 and 2") under the following conditions:

1. The operator of the landfill shall maintain the liners underlying Cell 3 and Phases 1 and 2, which were designed and constructed with an alternative liner as defined in § 258.40(a)(1) in accord with their current installed design in order to maintain the integrity of the liner system and keep it and the leachate collection system in good operating order. The operator of the landfill shall ensure that the addition of any liquids does not result in an increased leakage rate and does not result in liner slippage, or otherwise compromise the integrity of the landfill and its liner system, as determined by the State Director. In addition, the leachate collection system shall be operated, monitored, and maintained to ensure that less than 30 cm depth of leachate is maintained over the liner.
2. The operator of the landfill shall ensure that the concentration values listed in Table 1 of § 258.40 are not exceeded in the uppermost aquifer at the relevant point of compliance for the landfill, as specified by the State Director, under § 258.40(d).
3. The operator of the landfill shall monitor and report whether surface seeps are occurring and determine whether they are attributable to operation of the liquid application system. USEPA and VADEQ shall be notified in the semi-annual report of the occurrence of any seeps.
4. The operator of the landfill shall determine on a monthly basis the leachate quality in test and control areas with and without liquid addition. The operator of the landfill shall collect monthly samples of the landfill leachate and analyze them for the following parameters: pH, conductivity, dissolved oxygen, dissolved solids, biochemical oxygen demand, chemical oxygen demand, organic carbon, nutrients (ammonia, total Kjeldahl nitrogen, total phosphorus), common ions, heavy metals, and organic priority pollutants.
5. The operator of the landfill shall determine on a semi-annual basis the total quantity of leachate collected in test and control areas; the total quantity of liquids applied in the test areas and determination of any changes in this quantity over time; the total quantity of leachate in on-site storage structures and any leachate taken for offsite disposal.
6. Prior to the addition of any liquid to the landfill, the operator of the landfill shall perform an initial characterization of the liquid and notify USEPA and VADEQ of the liquid proposed to be added. The parameters for the initial characterization of liquids shall be the same as the monthly parameters for the landfill leachate specified in paragraph (c)(4) of this section. The operator shall annually test all liquids added to the landfill and compare these results to the initial characterization.
7. The operator of the landfill shall ensure that Cell 3 and Phases 1 and 2 are operated in such a manner so as to prevent any landfill fires from occurring. The operator of the landfill shall monitor the gas temperature at well heads, at a minimum, on a monthly basis.

8. The operator of the landfill shall perform an annual surface topographic survey to determine the rate of the settlement of the waste in the test and control areas.
9. The operator of the landfill shall monitor and record the frequency of odor complaints during and after liquid application events. USEPA and VADEQ shall be notified of the occurrence of any odor complaints in the semi-annual report.
10. The operator of the landfill shall collect representative samples of the landfill waste in the test areas on an annual basis and analyze the samples for the following solid waste stabilization and decomposition parameters: Moisture Content, Biochemical Methane Potential, Cellulose, Lignin, Hemi-cellulose, Volatile Solids and pH.
11. The operator of the landfill shall report to the USEPA Regional Administrator and the State Director on the information described in paragraphs (c)(1) through (10) of this section on a semi-annual basis. The first report is due within 6 months after the effective date of this section. These reporting provisions shall remain in effect for the duration of the project term.
12. Additional monitoring, record keeping, and reporting requirements related to landfill gas will be contained in a Federally Enforceable State Operating Permit ("FESOP") for the VA Project XL Landfills issued pursuant to the Clean Air Act, 42 U.S.C. 7401 *et seq*. Application of this site-specific rule to the VA Project XL Landfills is conditioned upon the issuance of such a FESOP.
13. This section applies until July 18, 2012. By July 18, 2012, the VA Project XL Landfills must return to compliance with the regulatory requirements which would have been in effect absent the flexibility provided through this section. If USEPA Region 3's Regional Administrator, the Commonwealth of Virginia and Waste Management agree to an amendment of the project term, the parties must enter into an amended or new Final Project Agreement for any such amendment.
14. The authority provided by this section may be terminated before the end of the 10-year period in the event of noncompliance with the requirements of paragraph (c) of this section, the determination by the USEPA Region 3's Regional Administrator that the project has failed to achieve the expected level of environmental performance, or the promulgation of generally applicable requirements that would apply to all landfills that meet or exceed the performance standard set forth in § 258.40(a)(1). In the event of early termination, USEPA in consultation with the Commonwealth of Virginia will determine an interim compliance period to provide sufficient time for the operator to return the landfills to compliance with the regulatory requirements which would have been in effect absent the authority provided by this section. The interim compliance period shall not exceed 6 months.

[66 FR 42449, Aug. 13, 2001, as amended at 66 FR 44069, Aug. 22, 2001; 67 FR 47319, July 18, 2002; 69 FR 18803, Apr. 9, 2004].

Appendix 4: United States Regulatory Overview on Project XL Concerning the Newly Developed Bioreactor Landfills

USEPA promulgated Subtitle D of the Resource Conservation and Recovery Act (RCRA), Criteria for Municipal Solid Waste (MSW) Landfills (40 CFR Part 258; 56 FR 50978), on October 9, 1991. These criteria establish minimum performance standards for the siting, design, operation, and post-closure management of landfills that receive non-hazardous solid waste. USEPA developed these regulations because landfills that receive non-hazardous solid waste have the potential to contaminate groundwater and create problems associated with gas migration. When developing Part 258 regulations, the USEPA recognized the potential advantage of leachate recirculation and allowed recirculation of leachate at landfills that were constructed with a liner specified in the regulations (a composite liner consisting of 0.61 m of clay having hydraulic conductivity <10 cm/s overlain by a geomembrane) and a leachate collection and recovery system (LCRS).

Subtitle D of RCRA establishes minimum standards for landfill design and operation. Congress delegated the administration of Subtitle D to the States, which can develop more restrictive regulations. Some states (i.e., New York and Pennsylvania) require double composite liners.

Recently, three developments that have affected the permitting and operation of bioreactor landfills: (i) Project XL, (ii) the Research, Development, and Demonstration (RD & D) rule, and (iii) requirements for gas collection at bioreactor landfills. USEPA implemented Project XL to facilitate the use of superior technology quickly. Permits for innovative and superior technologies are to be processed rapidly with input from USEPA. To date, four bioreactor landfill projects are approved as part of Project XL. These projects should provide additional data on specific aspects of bioreactor landfills including issues related to the introduction of supplemental liquids to landfills and leachate recirculation in landfills with alternative liners.

USEPA revised the Criteria for Municipal Solid Waste Landfills to allow States to issue research, development, and demonstration (RD & D) permits for new and existing MSW landfill units and lateral expansions. This rule allows Directors of approved state programs to provide a variance from certain MSW landfill criteria, provided that MSW landfill owners/operators demonstrate that compliance with the RD & D permit will not increase risk to human health and the environment over compliance with a standard MSW landfill permit. EPA finalized this alternative permit authority on March 22, 2004, and currently six states (Minnesota, Indiana, Illinois, Wisconsin, Michigan, and Missouri), have approved programs.

The RD & D rule adds flexibility to the existing 258 regulation to allow landfill owners to document that alternate approaches to design and operation of landfills may result in improved economics and/or environmental performance. The RD & D rule allows states to waive specific provisions of the MSW landfill criteria, including (i) operating criteria (except procedures for excluding hazardous waste and explosive gas control in Subpart C), (ii) design criteria in Subpart D, and (iii) final cover criteria in Section 258.6 (a) & (b). The rule allows alternate designs which might incorporate improvements in areas such as (i) liner system design and materials, (ii) leachate drainage and recirculation system design and materials, (iii) the addition of supplemental water to accelerate decomposition, and (iv) new liquid distribution techniques.

RD & D permits have an initial 3-year term, with three optional 3-year extensions, for a total of 12 years. The rule specifies that annual reports be submitted for all RD & D permits, and these annual reports summarize data obtained during the year and assess progress toward the goals of the specific RD & D permit at a site.

Specifically, related to bioreactor facilities, the rule provides that states can approve permits to allow the addition of non-hazardous liquids to a landfill unit constructed with an alternative liner (i.e., a liner that complies with the performance design criteria in 40 CFR 258.40(a)(1) rather than a liner that complies with the material requirements in 40 CFR 258.40(a)(2)). The State Director must be satisfied that a landfill operating under an RD & D permit will pose no additional risk to human health and the environment beyond that which would result from the current MSW landfill operating criteria. Under the RD & D rule permitting is still at the discretion of each state.

USEPA issued a final rule on National Emissions Standards for Hazardous Air Pollutants (NESHAPS) for landfills in January 2003 (Federal Register, January 16, 2003, 40 CFR Part 63, National Emission Standards for Hazardous Air Pollutants: Municipal Solid Waste Landfills, USEPA Final rule). Included in this rule are Maximum Achievable Control Technology (MACT) regulations that affect bioreactor landfills. In this rule, bioreactors are defined to include those landfills that add liquid, other than leachate and gas condensate, to reach a minimum average moisture content of at least 40% by weight to accelerate anaerobic biodegradation of the waste. Aerobic landfills are not included in this definition.

The rule requires that landfill gas collection and control systems begin operation within 180 days after initiating liquids addition, or within 180 days after the landfill moisture content reaches 40% by weight, whichever is later. This rule applies only to bioreactor cells that receive liquids other than leachate and that have a design capacity greater than 2.5×10^6 Mg or 2.5×10^6 m^3. Affected sites are required to submit startup, shutdown, and malfunction plans, and to track and report every 6 months any deviations from air pollution limits.

In summary, the operation of landfills with leachate recirculation has always been allowed under Part 258, but addition of liquids other than leachate and gas condensate has not been allowed. The addition of such liquids could be permissible under the RD & D rule or through Project XL. In all cases, whether a traditional Part 258 permit, a Project XL application, or an application under the RD & D rule, the ultimate authority to permit the construction and operation of landfills will rest with the states. The approach of the states has varied considerably, although many states have become more receptive to the operation of landfills as bioreactors.

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