Chapter 1
Introduction to Solid Waste Management

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Abstract An increase in population growth, industrial development, and urbanization has led to increasing solid waste generation. Complications associated with solid waste can be dated back to ancient history. The waste produced and collected in an urban area is called municipal solid waste (MSW), mainly associated with the wastes produced from domestic, industrial, commercial, and institutional areas. The amount and composition of waste vary by country. New and effective strategies are generally needed to design urbanization models, and policies are required for effective solid waste management. All aspects of waste storage, collection, transportation, sorting, disposal, and related management are included in solid waste management. It does not stop after collection only, but what needs to be done with the wastes is part of the important aspects of the whole management protocol. Basic waste data are included in this chapter. These include their types, sources, quantity, and compositions. Next, the functional elements of the waste management system are discussed, which among others, includes the aspects of storage, collection, transportation, recovery and processing, composting, thermal treatment, and the

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final disposal. The legislation related to waste is also discussed, followed by the descriptions of the integrated solid waste management.

Keywords Solid waste · Municipal Solid Waste (MSW) · Waste management · Recycling and recovery · Waste processing · Waste disposal

Acronyms

APCr	Air Pollution Control Residues
ASME	American Society of Mechanical Engineers
C&I	Commercial and industrial
C&D	Construction and demolition
CBA	Cost-Benefit Analysis
BFR	Brominated flame retardants
CFC	Chlorofluorocarbons
HCFC	Hydrochlorofluorocarbons,
EIA	Environmental Impact Assessment
EPA	Environmental Protection Act
EU	European Union
HFA	Humic and fulvic acids
ISWM	Integrated solid waste management
LCA	Life Cycle Assessment
MSW	Municipal solid waste
MFA	Material Flow Analysis
PWCS	Pneumatic waste conveyance system
RCRA	Resource Conservation and Recovery Act
RA	Risk Assessment
RMA	Rubber Modified Asphalt
SEA	Strategic Environmental Assessment
SoEA	Socio-economic Assessment
SA	Sustainable Assessment
S/S	Solidification/stabilization
TDA	Tyre-Derived Aggregate
UNEP	United Nations Environment Programme
US	United States
USEPA	US Environmental Protection Agency
UK	United Kingdom
VFA	Volatile fatty acids

Nomenclature

%	Percentage
$	American dollar
Per capita	head/person or individual

1.1 Introduction

An increase in population growth, industrial development, and urbanization has led to increasing solid waste generation. Solid waste is produced as results of activities from several sources such as residential areas, marketing places, restaurants and food areas, public and industrial installations, waterworks and sewage facilities, construction, and agricultural sites. Solid waste remains a critical issue in many countries. Complications associated with solid waste can be dated back to ancient history. Because of the new inventions, technologies, and services, waste has been changed quantitatively and qualitatively over time. Its generation rates and composition differ from one country to another and lifestyle. Several variables affect the characterisation of the waste based on the economic conditions, policies on waste management, industrial structure, lifestyle-changing and living standards, culture, and geography. Urbanization can be considered as one of the primary factors for increasing solid waste generation due to the urban population. New and effective strategies are generally needed to design urbanisation models, and policies are required for effective solid waste management.

Almost everything we do creates some form of waste [1]. The disposal of solid waste becomes a significant problem globally, especially in developing countries. The waste generation rate is generally proportional to the degree of economic growth and the age of the urban population. Despite this expansion, effective waste management remains a challenging task. Generally, only a small portion of the raw materials consumed will be used to make a product; the remainder will be thrown away.

All aspects of waste storage, collection, transportation, sorting, disposal, and related management are included in solid waste management. It normally involves an integrated approach covering all of the above activities. It does not stop after collection only, but what needs to be done with the wastes is part of the important aspects of the whole management protocol. The abundance of solid waste generated without proper management and handling can cause serious problems to a society, such as the spread of diseases, bad odour, and environmental pollution. Thus, a proper solid waste management system is necessary.

1.1.1 Definition of Solid Waste

Generally, solid waste is any substance in a solid form that is unwanted/unused and/or unvalued and is discarded or discharged for disposal. However, the definition varies by country. The US Environmental Protection Agency (USEPA) defined MSW as any amount of waste that contains any items thrown away after use, such as packaging products, plastic bags and papers, plastic bottles and containers, and batteries, which are generated from households, hospitals, schools, and institutions [1]. The Resource Conservation and Recovery Act (RCRA) of the United States, passed in 1976, defines 'solid waste' as garbage or refuse; sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility; and other discarded material resulting from manufacturing, commercial, mining, and agricultural operations, as well as community activities. The Indian rules for Management and Handling of solid waste in 1999 defined municipal waste as the materials that include commercial and residential wastes which are generated from municipal, industrial, and other sources.

The waste produced and collected in an urban area is called 'municipal solid waste' (MSW), mainly associated with the wastes produced from domestic, industrial, commercial, and institutional areas. In the United States, it is referred to as waste or garbage; and in the United Kingdom, it is referred to as rubbish. It is a form of waste made up of commonplace objects discarded by the general public. In Malaysia, municipal solid waste (MSW) is outlined as any scrap materials, other unwanted surplus substances, or rejected products that occur as a result of human activity, except scheduled wastes such as sewage and radioactive wastes, as defined by the Solid Waste and Public Cleansing Management Act 2007 (Act 672). The origin of solid waste influences its characteristics.

1.1.2 Sources of Solid Waste

There are a few different forms of solid waste that come from things that people throw away. MSW, or garbage, is made up of a variety of things that people discard. Packaging, food, furniture, electronics, yard trimmings, tyres, and appliances are among these products.

While there are several different ways to classify the waste sources, the following are the most common: domestic or residential, commercial (restaurants, grocery stores, other businesses), institutional (such as offices, schools, domestic hospital wastes), non-hazardous industrial (like offices, cafeterias, packaging, but not the process waste), construction and demolition (C&D), agricultural, and municipal activities (street cleaning, garden waste, etc.). In several countries, household waste accounts for 85–90% of total MSW material for the majority of local governments. MSW includes biodegradable organic matter and is one of the most difficult fractions to deal with because it is difficult to sort when combined with the other fractions.

1.2 Waste Generation and Quantity

Understanding the sources and types of solid wastes is required for the design and operation of the functional elements associated with solid waste management. Data on the composition and waste production rate rates are equally important.

For proper waste management, the quantity and composition of produced MSW are critical. The management of these waste materials is at the heart of all solid waste management activities at the local, regional, and subregional levels, as well as at the state and federal levels. As a result, it is important to learn as much as possible about MSW. The amount and composition of waste vary by country. Some of the data are presented below.

The US Environmental Protection Agency has released a number of statistics on waste management in the US [3]. Figure 1.1 depicts the per-person municipal solid waste generation per day between 1960 and 2018. MSW generation per person increased from around 1.22 kg per day in 1960 to 2.3 kg per day in 2018. Approximately 292 million tons of MSW were produced in 2018 (Fig. 1.1). Approximately 94 million tons of waste is recycled or composted, resulting in a recycling and composting rate of 32.1% (Fig. 1.2). In addition, other food management pathways processed about 18 million tons of food (6.1%) (Fig. 1.3). With energy recovery, over 34 million tons of MSW (11.8%) were combusted. Eventually, over 146 million tons (50.0%) were dumped on the ground (Fig. 1.3).

The generation, recycling, composting, combustion with energy recovery, and landfilling of MSW have all changed dramatically over the last few decades [2]. From under 10% of produced MSW in 1980 to 35.0% in 2017, the combined recycling and composting rate have increased (Fig. 1.2). Recycling alone (without

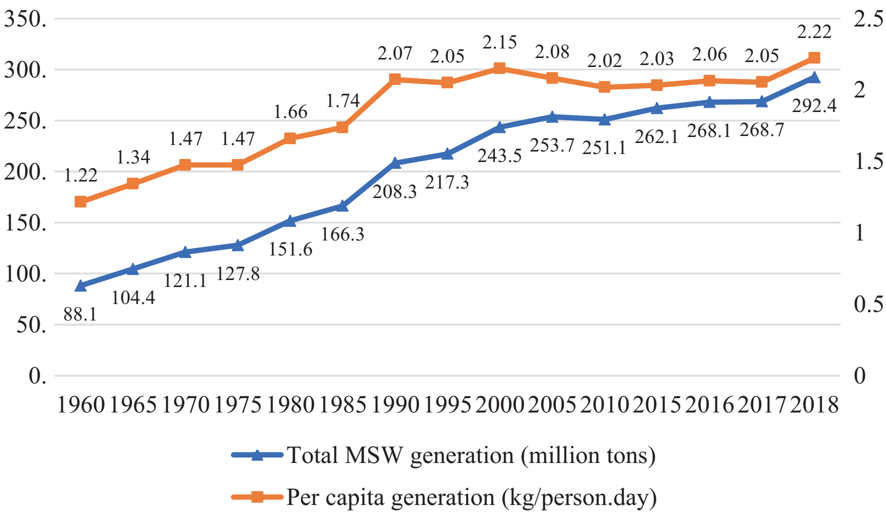


Fig. 1.1 MSW generation rates in the US from 1960 to 2018 [3]

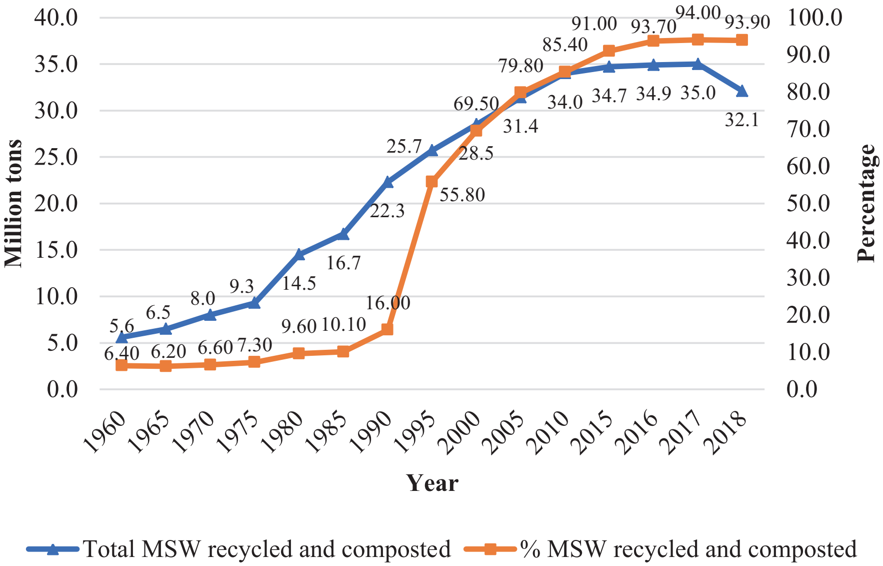


Fig. 1.2 Total municipal solid waste (MSW) recycled and composted in the US from 1960 to 2018 [3]

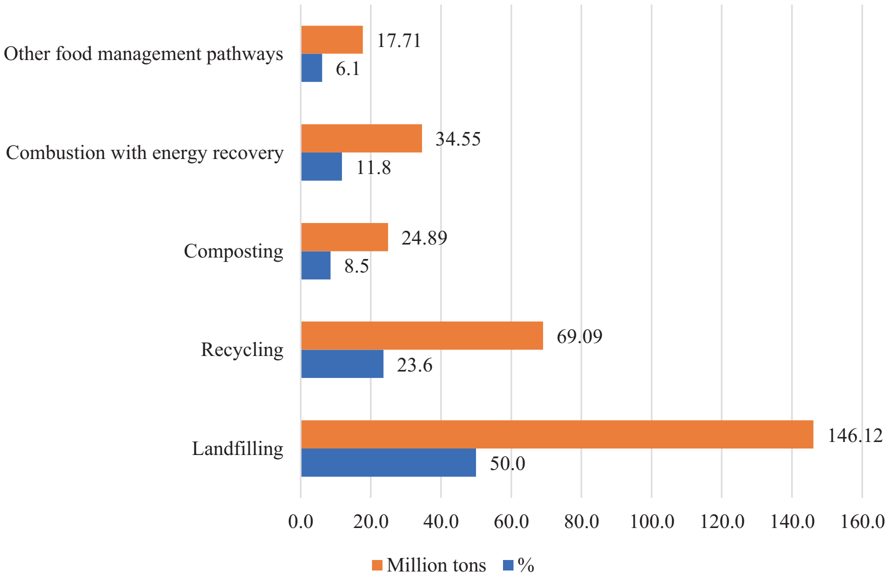


Fig. 1.3 Management of municipal solid waste (MSW) in the US in 2018 [3]

composting) increased from 14.5 million tons (9.6% of MSW) in 1980 to 69 million tons (23.6%) in 2018. Despite the fact that more tons of waste were recycled in 2018 than ever before, the recycling rate fell to its lowest level since 2006. Composting was almost non-existent in 1980, but by 2018 it had risen to 24.9 million tons (8.5%).

USEPA revised its food calculation methodology in 2018 to better capture flows of surplus food and food waste in the food system [3]. As shown in Fig. 1.3, other food management pathways accounted for 17.7 million tons (6.1%) of the total. In 1980, combustion with energy recovery accounted for less than 2% of total generation or 2.8 million tons. In 2018, 34.6 million tons of MSW were burnt with energy recovery, accounting for 118% of the total MSW produced. From 145.3 million tons in 1990 to 146.1 million tons in 2018, the overall volume of MSW sent to landfills has risen by under one million tons.

In Hong Kong, about 3700 tons of putrescible waste is dumped daily in landfills in 2019 [4]. The highest percentage of MSW generated in Hong Kong was a putrescible waste. In 2019, a total of 5.71 million tons of solid waste was disposed of at strategic landfills. The average daily quantity was 15,637 tons per day (tpd), down 2.8% from the previous year (Table 1.1). Domestic, agricultural, commercial and industrial (C&I) waste are all contained in MSW. The sum of MSW disposed of in 2019 was 11,057 tpd (4.04 million tons), down 3.2% from 2018. The shift can be attributed in part to local social unrest, which wreaked havoc on society and caused the local economy to contract in the second half of 2019. Excluding the population growth from the equation, the MSW disposal rate was 1.47 kg/person/day in 2019 versus 1.53 kg/person/day in 2018. Domestic waste makes up the bulk of MSW. In 2019, it disposed of 6554 tpd (2.39 million tons), a decrease of 2.4% from 2018. In comparison, the volume of C&I waste disposed of in 2019 was 4503 tpd (1.64 million tons), down 4.5% from 2018. In general, the amount of C&I waste produced is proportional to the rate of consumptions. The decline in C&I waste disposal in 2019 may be attributed in part to the local economy's contraction.

The changes in the per capita municipal solid waste (MSW) production between 1995 and 2018 in the EU is presented in Table 1.2 [5]. Table 1.3 presents the rate of MSW generation in Europe [6]. Also, Eurostat statistics reported that in 2019, 1.38 kg of municipal waste per capita/day were generated in the EU, and 48% of municipal waste was recycled (material recycling and composting) [7].

Table 1.1 Hong Kong's total solid waste at a landfill in 2019 [4]

Waste category		Average daily quantity (tons per day)	Year-on-year growth rate
1	Municipal solid waste (MSW)	11,057	−3.2
	(i) Domestic	6554	−2.4
	(ii) Commercial and industrial	4503	−4.5
2	Construction waste	3946	−3.3
3	Special waste[a]	635	−8.1
4	Total waste received at landfill	15,637	−2.8

[a]Does not include special waste not disposed of at landfill

Table 1.2 Waste generation rate based on region [5]

Region	MSW generation rate (kg/capita/day)	Region	MSW generation rate (kg/capita/day)
Asia		*Oceania*	
Central	0.93	Australia and New Zealand	1.64
Eastern	1.32	Melanesia	3.23
South-eastern	1.26	Polynesia	3.70
Southern	1.37		
Western	1.89	*Africa*	
		Northern	1.12
Europe		Eastern	0.79
Eastern	1.01	Middle	0.52
Northern	1.32	Southern	0.90
Southern	1.29	Western	0.49
Western	1.62		
America			
Caribbean	2.14		
Central	1.59		
South	1.18		
Northern	2.63		

According to the World Bank [8], the world generates 2.01 billion tons of urban solid waste per year, with at least 33% of it not being treated in an environmentally friendly manner. The average amount of waste produced per person per day is 0.74 kg, but it varies widely, varying from 0.11 to 4.54 kg. While having just 16% of the world's population, high-income countries produce about 34% of the world's waste or 683 million tons. By 2050, the total amount of waste generated in low-income countries is estimated to increase by more than threefold (Fig. 1.4).

As reported by the United Nations Environment Programme (UNEP), Association of Southeast Asian Nations (ASEAN) countries have a total population of 625 million people, accounting for 8.8% of the global population. By 2020, the population is predicted to reach 650 million inhabitants, with urban areas account for more than half of the total population is concentrated in this region. According to reports, Asian cities will produce the most waste in 2025, with 1.8 billion tons (up from 0.28 billion tons in 2012) [9].

In ASEAN, the MSW generation rate is 1.14 kg/capita/day (Table 1.4). The following is the order of total annual MSW generation: Indonesia produces the most urban waste, with 64 million tons per year, followed by Thailand (26.77 million tons per year), Vietnam (22 million tons per year), the Philippines (14.66 million tons per year), Malaysia (12.84 million tons per year), Singapore (7.5 million tons per year),

Table 1.3 MSW generation rate in Europe [6]

Country	Toons per year
Austria	61,225
Belgium	63,152
Czech Republic	25,381
Denmark	20,982
Estonia	24,278
Finland	122,869
France	323,474
Germany	400,072
Hungary	15,908
Iceland	1067
Italy	163,995
Korea	180,367
Latvia	2533
Lithuania	6644
Luxembourg	10,130
Netherlands	141,024
Norway	11,197
Poland	182,006
Portugal	14,739
Slovak Republic	10,607
Slovenia	5517
Spain	128,959
Sweden	141,626
Turkey	75,535
United Kingdom	277,281

Myanmar (0.84 million tons per year), and Lao Peoples' Democratic Republic (PDR; 0.07 million tons per year). Organic waste accounts for the majority of MSW in all ASEAN countries (about or more than 50%), with the exception of Singapore, where organic waste represents just 10.5% of the total MSW. Other types of waste, such as plastic, metals, and paper are popular in MSW dumps. Aside from MSW, emerging waste sources in ASEAN countries include healthcare waste, e-waste, industrial waste, and construction and demolition waste.

Looking ahead [8], global waste is projected to reach 3.40 billion tons by 2050, more than twice the rate of population increase over that time period. Overall, waste generation and profits have a good relationship. In high-income countries, daily waste generation per head is expected to rise by 19% by 2050, compared to 40% or more in low- and middle-income countries.

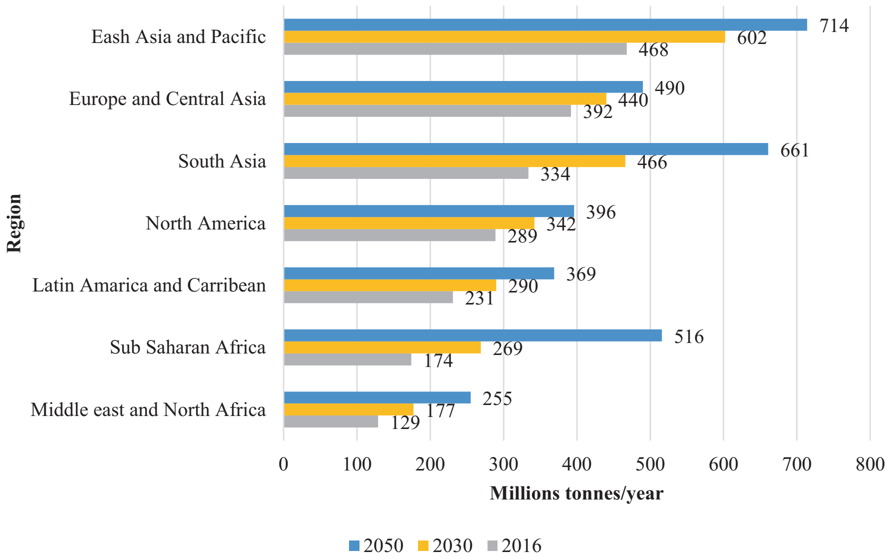


Fig. 1.4 Generation municipal solid waste by region [8]

Table 1.4 MSW generation in ASEAN countries [9]

No	Country	MSW generation		
		kg/capita/day in 2009	Annual MSW in 2009 (metric tons)	Projected MSW in 2025 (kg/capita/day)
1	Brunei Darussalam	1.40	210,480	–
2	Cambodia	0.55	1,089,429	–
3	Indonesia	0.77	64,000,000	1.0
4	Lao PDR	0.69	77,380	0.80
5	Malaysia	1.17	12,840,000	1.40
6	Myanmar	0.47	12,840,000	0.60
7	Philippines	0.53	14,660,000	0.80
8	Singapore	1.10	7,514,500	1.10
9	Thailand	1.10	26,770,000	1.50
10	Vietnam	0.57	22,020,000	0.70

1.3 Types and Composition of Solid Waste

1.3.1 Types of Solid Wastes

In their study, Hussein et al. [10] had established that the majority of municipal solid waste produced in the developing country originates from households (55–80%), succeeded by the market or commercial areas (10–30%). The latter is made up of a variety of variable quantities produced by industries, streets, institutions, and a variety of other sources. Solid waste from such sources is usually high and heterogeneous. In general, waste characteristics differ depending on the sources of waste. It is a significant need for the classification and characterisation of these wastes for any effective treatment or disposal methods. The separating of generated solid wastes is considered as one of the most important and effective methods of solid waste management to provide useful information about the quality of the separated wastes for any potential utilisation. Table 1.5 presents the common source and types of solid waste.

1.3.2 Composition of Solid Waste

Social and economic factors, such as population growth, demand growth, changes in consumption habits, and waste management system technological advancement, have all had a significant impact on the waste aspect [11]. The composition of waste depends on locality and differs according to the income class, indicating different consumption trends (Fig. 1.5) [8]. High-income countries produce less food and green waste, accounting for 32% of total waste, and more dry waste that can be recycled, such as plastic, paper, cardboard, metal, and glass, accounting for 51% of total waste. Food and green waste are produced in 53% and 57% of middle- and low-income countries, respectively, with the proportion of organic waste rising as economic development levels decline. In low-income countries, just 20% of the materials used in building are recyclable. Aside from waste streams that are associated with wages, there is little variation in waste streams across regions. With the exception of Europe, Central Asia, and North America, which produce more dry waste, all regions produce about 50% or more organic waste on average. A standard urban solid waste in China contains 55.9% food residue, 8.5% paper, 11.2% plastics, 3.2% textiles, 2.9% wood waste, 0.8% rubber, and 18.4% non-combustibles [12].

In the US, during 2018, some 8.9% of the total MSW was generated, consisted of textiles, rubber, and leather materials (Fig. 1.6) [3]. The average daily MSW (by composition) at landfills in Hong Kong in 2019 is shown in Fig. 1.7.

MSW compositions in ASEAN countries are given in Table 1.6. It can be noted that food waste/organics constitute between 45% and 60% in all ASEAN countries, except Myanmar (73%). They are mostly disposed of in a landfill or dumpsite, except for Singapore.

Even though there are many variations, however, MSW can be broadly divided into several types such as food waste, paper, plastic, textiles, glass, wood, metal, metal cans, rubber, leather, scraps, and bulky waste.

Table 1.5 Sources of solid wastes within a community

Source	Typical activities or locations where waste is produced	Types of wastes
Residential	From various types of houses with different income groups	Food wastes/organics, paper, cardboard, plastics, textiles, leather, yard wastes, wood, glass, bottles, tin cans, drink cartons, aluminium, other metals, ashes, garden waste, special wastes (including bulky items like discarded furniture, domestic e-waste, household hazardous wastes, batteries, oil, and used tyres
Commercial	Restaurants, supermarket, mini market, grocery shops, hotels, motels, shops, service stations, automobile workshops, laundrette, etc.	Paper, plastics, cardboard, wood, food waste, glass, metals, special wastes (see above), hazardous wastes, etc.
Institutional	Schools, higher leaning institutions, prisons and government detention centres, hospitals, governmental offices, training centres, etc.	As above in commercial
Construction and demolition	New construction sites, road repair and renovation sites, broken pavement, demolition of buildings	Concrete, wood, steel, tar, glass, dirt, etc.
Municipal services (excluding treatment facilities)	Landscaping wastes, street cleaning, grass cutting, tree trimming, drain cleaning, dead animal wastes, parks and beaches, other recreational areas	Street rubbish, sidewalks, vacant lots, trees branches, debris, grass, general wastes from parks, beaches, and recreational areas, etc.
Treatment plant sites; municipal incinerators	Treatment systems for water, wastewater, and industrial waste, etc.	Wastes from treatment plants, mostly sludges, bottom and fly ashes, and slag
Municipal solid waste	All of the above	All of the above
Industrial	Construction, manufacturing – light and heavy, fabrication, chemical plants, refineries, power plants, process waste, etc.	Wastes from industrial processes, scrap materials, etc. Non-industrial wastes – rubbish, food wastes, ashes, special wastes (see commercial), hazardous wastes
Agricultural	Dairies, feedlots, farms, field and row crops, orchards, vineyards, etc.	Spoiled food wastes, agricultural wastes, rubbish, used packaging from fertiliser, etc., hazardous wastes

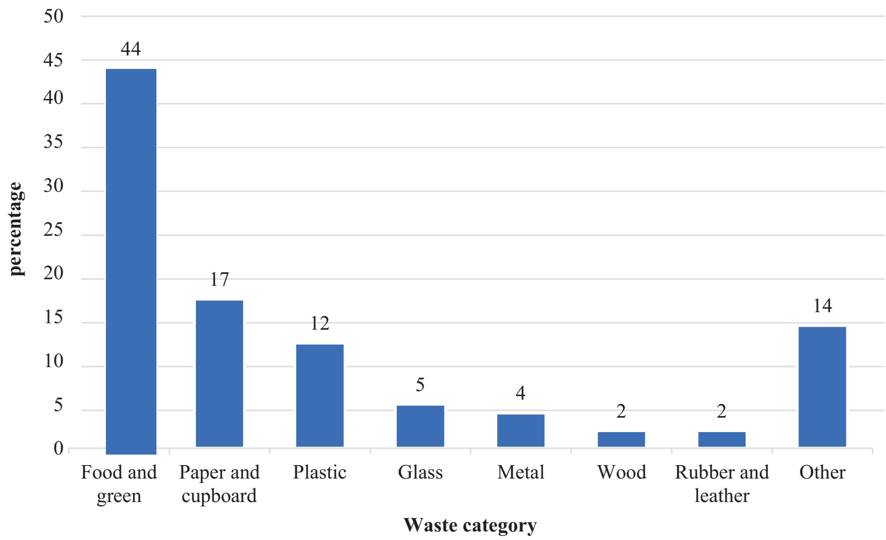


Fig. 1.5 Global waste composition [8]

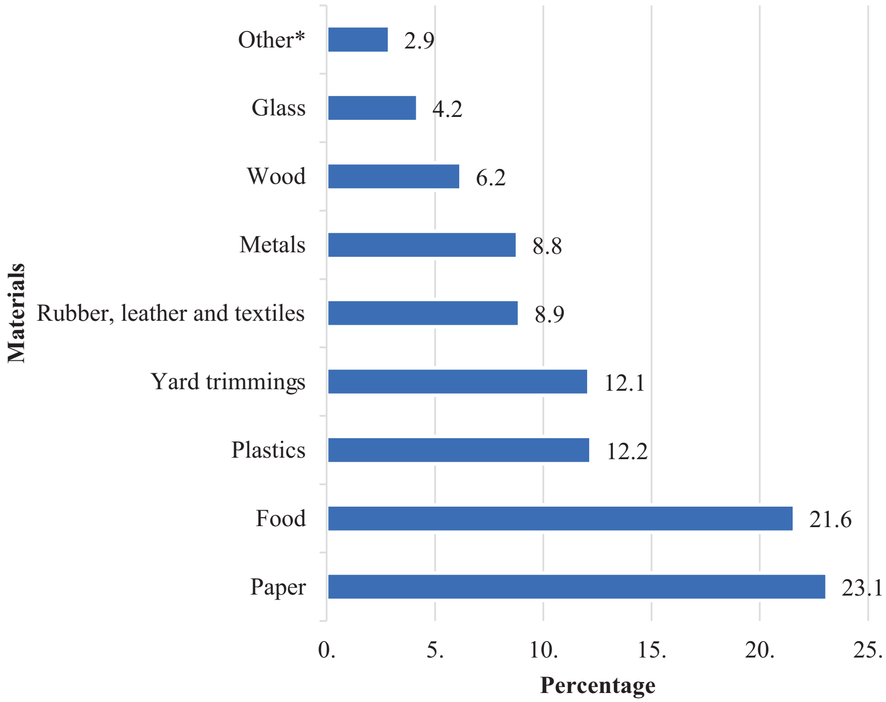


Fig. 1.6 By material distribution of MSW stream generated in the United States in 2018 [3]

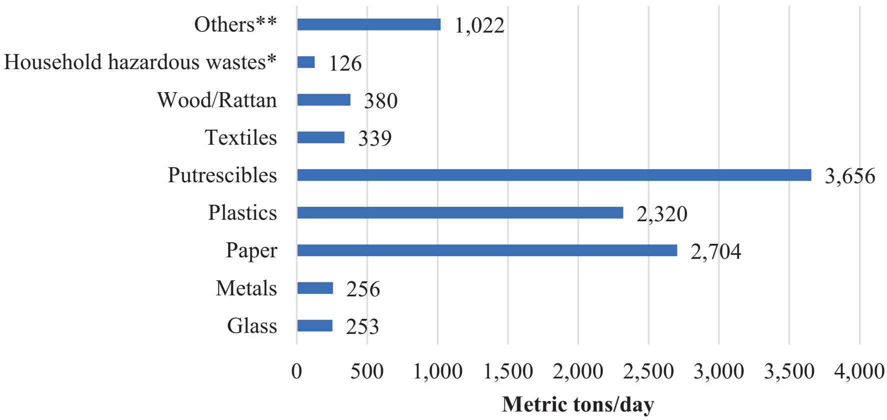


Fig. 1.7 Average daily MSW (by composition) at landfills in Hong Kong in 2019 [4]

1.4 Special Types of Solid Waste

1.4.1 Industrial Solid Waste

Residues are produced by almost every industry. Industrial solid waste is any material that is made useless during manufacturing and processing processes, as well as any waste generated by the industrial operation. Depending on the nature of the industries or businesses, solid waste may be in the form of hazardous or non-hazardous. The hazardous waste, such as waste chemicals, containers, sludge, solvents, etc., is managed as a separate waste stream that requires special handling and disposal. This is not covered in this chapter. Although the amounts can vary, the non-hazardous consists mostly of cupboard and paper waste, non-hazardous scrap metals, garbage, and related wastes and materials to residential waste.

The origin of the waste generated by industry has a substantial effect on the composition of the waste produced. Animal hide manufacturing, for example, generates a lot of biodegradable waste (animal parts), while construction generates a lot of excavated dirt, rock, and demolition waste (bricks, stones, wood, glass, etc.). As a result, industrial waste is normally treated and disposed of by the industry, which also employs advanced technologies.

There is no universally accepted classification system for industrial solid waste. However, it is more useful to divide the industry into three large groups, each with distinct types of operation and, as a result, distinct waste-generating characteristics. Extractive industries, basic industries, and manufacturing are the three groups.

Table 1.6 MSW composition in ASEAN countries [9]

No	Country	MSW composition (%)									
		Food/Organics	Paper	Plastic	Metal	Glass	Textile	Rubber	Grass/wood/etc.	C&D[a]	Others
1	Brunei Darussalam	36	18	16	4	3					
2	Cambodia	60	9	15		3	1	1			
3	Indonesia	60	9	14	4.3	1.7	3.5	5.5			2.4
4	Lao PDR	64	7	12	1	7	5	3			
5	Malaysia	45	8.2	13.2		3.3					27.3
6	Myanmar	73	2.24	17.8		0.5	1.1				5.2
7	Philippines	52	8.7	10.6	4.2	2.3	1.6				
8	Singapore	10.5	16.5	11.6	20.8	1.1	2.1		8.6	16.9	11.9
9	Thailand	64	8	17.6	2	3	1.4	1	1		
10	Vietnam	55	5	10	5	3		4			

[a]C&D – Construction and demolition

1.4.1.1 Extractive Industries

There are factories where raw materials are extracted from the earth and sold in their natural state. Mining, quarrying, agriculture and food, and logging are four extractive industries that generate significant amounts of solid waste. Solid wastes produced by such factories are simply natural components or products. These factories concentrate wastes in particular areas; the wastes are natural products of the earth and its living organisms, but they vary in nature, with some being inert materials and others being biodegradable organic matter.

(a) Mining. Waste produced during the extraction, beneficiation and processing of minerals is referred to as mining waste. The Mining Waste Exclusion under Subtitle C of the Resource Conservation and Recovery Act (RCRA) has exempted most extraction and beneficiation wastes from hard rock mining (the mining of metallic ores and phosphate rock) and 20 particular mineral processing wastes (see sidebar below) from federal hazardous waste regulations [13].

Mineral capital accounts for more than 70% of all resources used in the global economy (in terms of volume) [14]. Strong rocks, gravels, clays, pebbles, sands, limestones, chalks, siftings of fine fractions, dump tailings of ferrous and non-ferrous metal ores, sulphur ores, apatite–nepheline concentrates, coal wastes, halite flotation wastes, phosphorite screenings, phosphoric ore fines, and other mining wastes are examples. Mining and refining sectors are among the most polluting industries, with wastes accounting for more than 90% of mined mineral raw materials. Mine dumps are technogenic geological structures made of rocks or sediments that differ from background rocks in composition (chemical, particle size, bacteriological) and properties (physical and mechanical, capacity for filtration and absorption). The shapes and types of mine dumps are mainly determined by the technical processes used [14].

Per year, mining solid waste amounts to more than a billion tons, with an additional 23 billion tons of cumulative waste from the previous 30 years distributed across the United States. The extraction and processing of mineral ores are expected to produce 1.6 billion metric tons (1.8 billion tons) of mineral processing waste in the United States per year [15]. Mineral processing waste accounts for close to half of all solid waste generated in the United States each year. Mineral wastes accumulated over decades of past mining operations are estimated to be worth at least 50 billion metric tons (55 billion tons) [16]. Despite the fact that many mining sites are in remote locations, virtually every state has large amounts of mineral processing waste.

(b) *Quarrying.* Quarrying is the method of removing stone from the ground. This form of extractive industry involves open pit or strip mining, as well as the quarrying of glass sand, stone, and sand and gravel. The issue of solid waste is similar to that of mining, except that the amounts involved are much lower (approximately 0.5–5% of mining wastes).

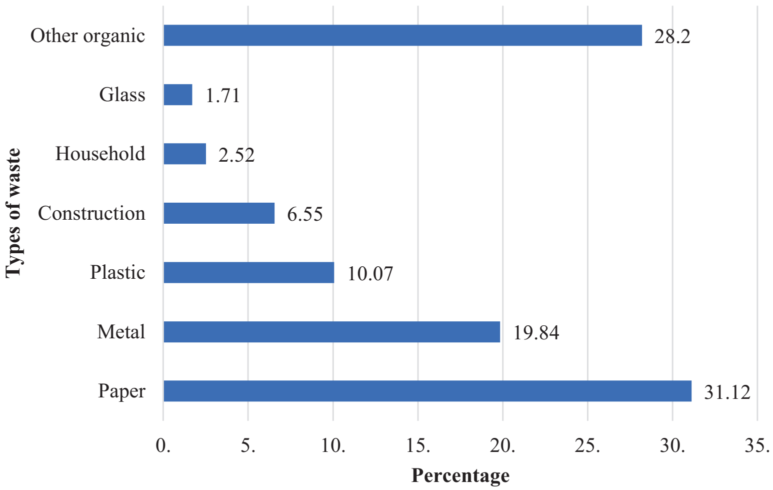


Fig. 1.8 In 2014, the following materials made up the majority of waste produced by mining, quarrying, and oil/gas extraction in the United States [17]

According to the US Chamber of Commerce, the share of waste produced by mining, quarrying, and oil/gas extraction in the United States in 2014 was broken down by content (Fig. 1.8). It was found that more than 30% of the total waste in the mining, quarrying, and oil/gas extraction industries consisted of paper.

(c) *Agriculture.* Agriculture is one of the most important sectors in the world. Agricultural waste refers to discarded or unsaleable products resulting solely from agricultural activities that are directly linked to growing crops or raising animals for the primary purpose of benefit or livelihood. Animal wastes are biomass materials because they are extracted from plants that have been eaten as food, either directly or indirectly via the food chain. Crop and orchard residues, as well as forest trash, make up plant residues. The amount of plant residue left on farms far outnumbers the number of crops brought to market. Grapefruit-bearing plants, vegetables, date palm and palm oil fronds, grass, stubble, leaves, hulls, tree limbs, and other litter are examples of farm waste. The majority of these wastes are burned to eradicate plant diseases and pests; however, a limited portion is used for mulch, ensilage, animal bedding, and other purposes.

In 2012, the biggest concentrated animal feeding operations (CAFOs) generated 369 million tons of manure, about 13 times the waste produced by the whole US population of 312 million people [18]. Between 2013 and 2016, the overall EU livestock population remained stable, accounting for 131 million livestock units [19].

Because of the large quantities generated and the concentration of animals at central processing points, livestock, and poultry wastes (mostly manure) are a major source of concern. A feedlot with 10,000 cattle produces approximately 300 tons

(270 metric tons) of solid waste/day, while a poultry operation with 270,000 hens produces approximately 40 tons (36 metric tons) of manure per day.

(d) *Food*. According to studies [20], about 30% and 40% of all food produced in the United States is thrown away. This equates to a total of 133 billion pounds ($161 billion). In the United States, overall food loss is estimated at $218 billion, while in Canada, it is $31 billion. Food waste accounts for 21–33% of agricultural water consumption in the United States. Wasted food is grown on 18–28% of our productive cropland. Each year, the USDA reports that about 4% of planted crops, or 66,500 acres, go unharvested. Across all forms of produce, manufacturing and processing (such as canning, freezing, drying, and pre-cutting) results in around 4% food loss. Despite the fact that manufacturing processes are becoming more efficient, the amount of food waste generated by expired, recalled, or unsold full packaged products are staggering. In terms of supermarket food waste, 10% of food in grocery stores, or 43 billion pounds, will never be consumed. In the case of produce, about 12% of fruit and 11.5% of vegetables are never sold, and food waste accounts for 30% of a grocery store's garbage [20].

(e) *Logging*. Logging is a form of data collection. Non-commercial sections of trees and brush, such as tops and cut-offs, are used in logging waste. Slash is a term used to characterize this sort of material. On an average, every year about 25 million tons of logging debris are left in the forest, or about 1 ton for every 1000 board feet of logs harvested. This debris is a breeding ground for insects and tree diseases as well as a serious fire hazard. Any woody material can be sold as firewood or as a source of fuel for outdoor wood boilers.

1.4.1.2 Basic Industries

Basic industries use extractive industries' products as raw materials and refine them into refined materials that other industries may use to make consumer goods. Metal sheets, tubes, cables, coke, industrial chemicals, paper, lumber and plywood, plastics, bottles, and synthetic fabrics are examples of products in this industrial group. The composition of solid waste produced by these industries is more diverse. Only a small percentage of refined products end up as solid waste, and all of the waste can be recycled right in this industrial category. The seven most popular industries that produce solid waste are listed below.

(a) Metals. Mined ores are transported to a manufacturing facility, where the metal is processed and refined. This process produces substantial solid wastes, such as slag, which accounts for 20% of steel ingot output. Aluminium and copper, on the other hand, each generate about 5 million tons (4.5 million metric tons) of inert waste each year. A subsequent step, in which ingots are shaped into shapes, produces lesser amount of solid wastes. The majority of these are product trimmings and residues from other refined materials used in the process.

(b) Chemicals. This industry creates the largest range of solid wastes, from slurries to dry solid cake, flammable organic tars to inert inorganic salts, hazardous materials like chromates to popular salt. They all come from one of three places: unreacted raw materials, pollutants in raw materials, or chemical reaction by-products. Organic solid wastes are often tars that form as unwanted by-products of chemical reactions, while inorganic solid wastes are often unreacted raw materials or contaminants in the raw material or mine.

(c) *Paper*. The processing of paper and paperboard produces two types of solid waste: residues from the materials used in the process and residues from the finished product. The first category includes tree bark, wood fibre, paper pulp, and inert filler, while the second category includes trimmings and waste. In their analysis, Simao et al. [21] reported that global pulp and paper mill production is increasing every year. As a result, the amount of waste generated is also rising. In 2013, world paper production totalled 403 million metric tons, while pulp production totalled 179 million metric tons, with the top 10 pulp producers being the United States, China, Canada, Brazil, Sweden, Finland, Japan, Russia, Indonesia, and Chile. The annual waste generation is most likely in excess of 1 million metric tons.

(d) *Plastics*. Plastics are a type of material that can be used in a number of ways. Plastic wastes are mostly trimmings or off-spec materials produced by basic factories that turn basic chemicals into plastic sheets or other forms used by fabricators. According to the USEPA, 13.7 million tons of plastics were discovered in durable goods in 2018 (Fig. 1.9) [3].

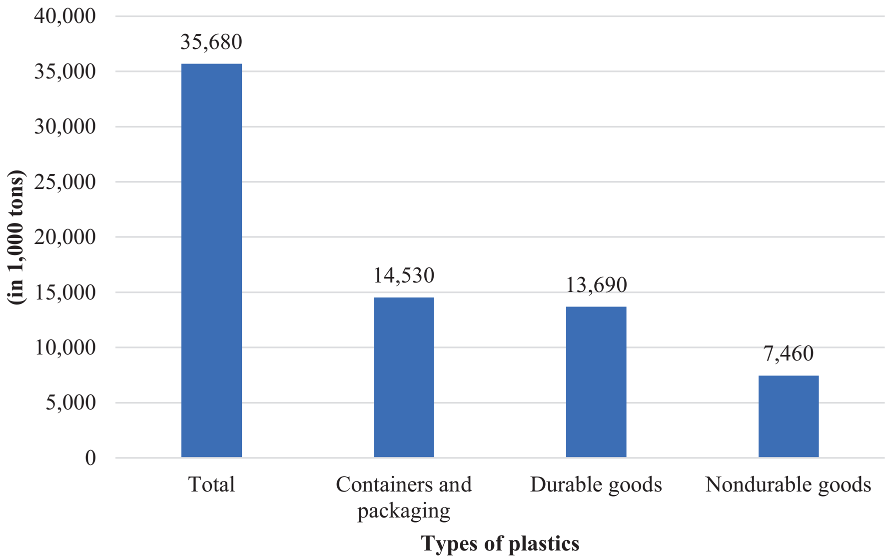


Fig. 1.9 The US municipal solid waste: plastics generation by category 2018 [3]

Table 1.7 MSW glass products in the US, 2018 [3]

Category of product	Amount generated (thousand tons)	Recycled amount (thousand tons)	%	Combustion (with energy recovery) (thousand tons)	Landfilled (thousand tons)
Durable goods[a]	2460	<100	<0.05%	330	2130
Packaging and containers					
Bottles (beer and soft drink)[b]	4650	1840	39.6	550	2260
Bottles (wine and liquor)	1810	720	39.8	210	880
Other bottles and jars	3330	500	15.0	550	2280
Glass containers (total)	9790	3060	31.3	1,310	5420
TOTAL GLASS	12,250	3060	25.0	1,640	7550

[a]Appliances, furniture, and consumer electronics made of glass
[b]Inclusive of carbonated and non-carbonated drinks

(e) *Glass*. In the basic glass sector, the bulk of solid waste is recycled within the industry. Cullet (glass fragments) from breakage and trimming, off-grade material, and slag from the purification of glass sand make up the majority of this waste. Table 1.7 shows the MSW glass goods in the United States in 2018 [3].

(f) Textiles. Cotton, linen, and wool are the three most important essential textile industries. Cotton textile mills produce wastes like strapping and burlap used in baling, as well as comber wastes and fibres damaged during storage and shipping, all of which are recycled. Linen textile mills produce waste that is similar to flax waste. Wastes such as fibre, twine, wool fat, and dirt are produced during the preparation of wool. Residues from spinning, weaving, and trimming operations also contribute to the overall solid waste image.

While textile waste is not considered hazardous, the waste generated by the textile and fashion industries has significant environmental implications. Textiles and garments that have been discarded may be processed to be reused and recycled. Textile waste is typically disposed of in landfills. Belgium had the largest amount of textile waste sent to landfills in 2016, with an average of 8.4 kg per capita, according to data (Fig. 1.10) on waste generation in European Union (EU) countries. Following Belgium, Czechia, Portugal, Italy, and Austria had the most landfilled textile waste per person [22].

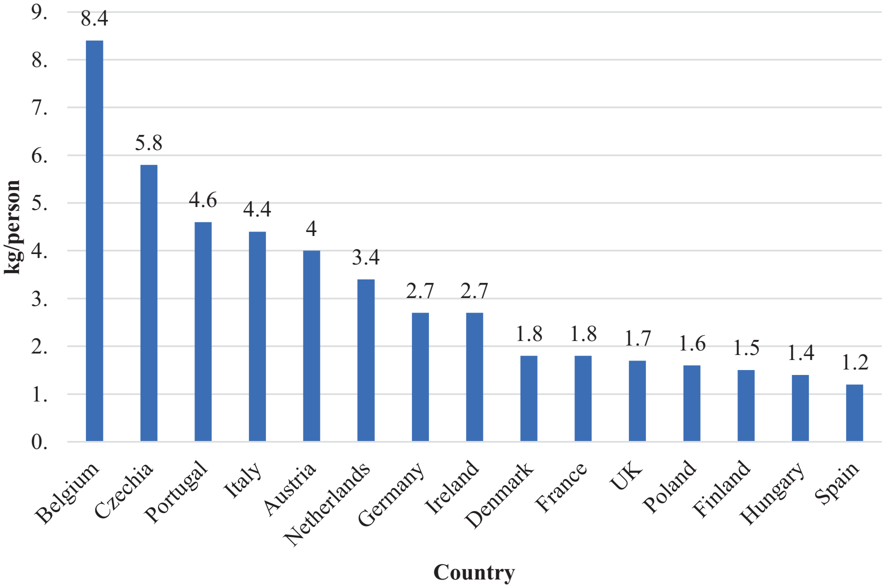


Fig. 1.10 The yearly total quantity of landfilled textile waste per person in the European Union (EU) in 2016, by country (in kg) [22]

(g) Wood Products. Furniture, other durable goods (e.g., cabinets for electronic equipment), wood packaging (crates, pallets), and other miscellaneous items are all sources of wood in municipal solid waste (MSW). In 2018, there were 2.8 million tons of wood in MSW that were combusted. In that year, 8.2% of MSW was combusted with energy recovery. Landfills received 12.2 million tons of wood in 2018. This accounted for 8.3% of all MSW landfilled in that year [23].

Every year, approximately 7.4 million tons of post-consumer wood waste are produced in the United Kingdom. Timber-based wastes from furniture production, fencing, infrastructure (such as telegraph poles and railway sleepers), agriculture and horticulture, and the do-it-yourself (DIY) sectors are all included in this figure. Although it is vital to optimizing material recovery, there are concerns about polluted wood, increased environmental impacts from recovery paths, and addressing the issue of how to better handle specific waste wood sources [24].

1.4.1.3 Manufacturing Industries

Conversion and fabrication industries make up this manufacturing market. They transform basic industry products into goods that are purchased by the general public. The solid waste generated by these industries primarily comes from the residues of the raw materials used by these industries. Furthermore, unlike simple industries, which can recycle most of their own rejects and trimmings, industrial industries can rarely use such residual wastes, and must rely on a secondary industry to reclaim them. However, the steps needed to transfer goods from one business sector to another place create a secondary solid waste burden on the recipient (in the form of packaging and containers). Since the number of manufacturing industries and the resulting variety of solid wastes produced is so large, only a few representative categories are discussed here.

(a) *Packaging*. The packaging industry uses a variety of materials, including aluminium, steel, glass, plastics, cardboard, corrugated paperboard, and plastic and paper laminates. The solid waste stream produced by this industry is dependent on the type of material used and the variety of activities performed at the facility, and it accounts for only a small portion of the total material used.

In 2018, 24% of the US packaging industry's market value was generated from the corrugated segment. The overall value of the US packaging industry was expected to be about 170 billion dollars that year, up from 144 billion dollars in 2011 [25].

(b) *Automotive*. Automotive industries generate a lot of solid waste. The discarded wastes include various components as tyres, generators, batteries, carburettors, wheels, bumpers, hub caps, and hundreds of other products that make up an automobile are by far the most significant component of automobile assembly plant waste. Painting and upholstering often add a jar to the solid waste stream, as well as material residues.

In 2020, vehicle sales were forecast to decline to just under 64 million units, down from nearly 80 million units in 2017. The sector has seen a downward trend as the global economy has slowed, and the coronavirus pandemic has spread through all major economies. The two most critical divisions of the auto industry are commercial vehicles and passenger cars. In terms of both sales and demand, China is one of the world's largest auto markets. In 2018, China's automotive sales dropped for the first time; the industry crashed in February 2020 but is now showing signs of recovery [26].

(c) *Paper Products*. Paper products, such as books, magazines, facial and toilet tissue, paper towels and napkins, and newspapers, created high-quality solid waste from paper trimmings and filled paper residues. They can be recycled in secondary industry.

In 2025, the market value of paper goods in the United States is expected to reach approximately US$109 billion, up from an approximate market value of US$81 billion in 2018 [27].

(d) Hardware. This is the metals industry, which manufactures machines, tools, utensils, and devices that are used by all forms of companies and the general public. Trimming and sizing of tubes, plates, and structural forms, boring and

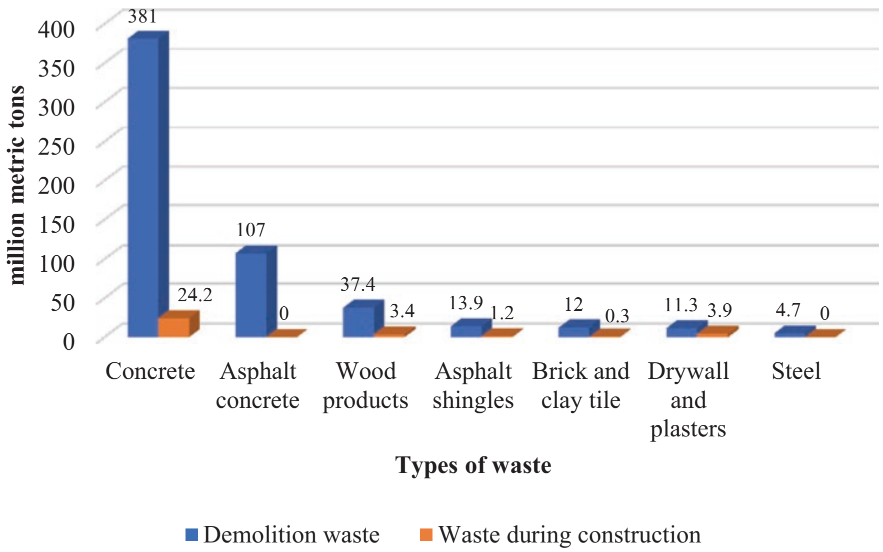


Fig. 1.11 The amount of material debris produced during construction and demolition in the United States in 2018 is depicted in Fig. 1.11 [3]

machining of metals, and miscellaneous residues from casting and forging processes make up the majority of the solid waste produced by this industry.

(e) Soft Goods. Leather, textiles, and plastics are used to make commercial goods in this industry. The residues from the processing of the materials are the most significant source of solid waste.

1.4.2 Construction and Demolition Waste

1.4.2.1 Definition

Materials that are unwanted or created during construction, demolition, or reconstruction activities of buildings, roads, and bridges are referred to as 'construction waste'. Concrete, wood, metals, bricks, glass, rocks, and asphalt are among the most popular heavy and bulky materials used in construction and demolition.

1.4.2.2 Quantity

The amount of construction and demolition waste differs from country to country based on the difference in the activities. Some of the statistics are discussed here.

In the United States, building waste accounts for one-third of all waste (2020, *Recycling magazine*). The amount of construction and demolition waste generated

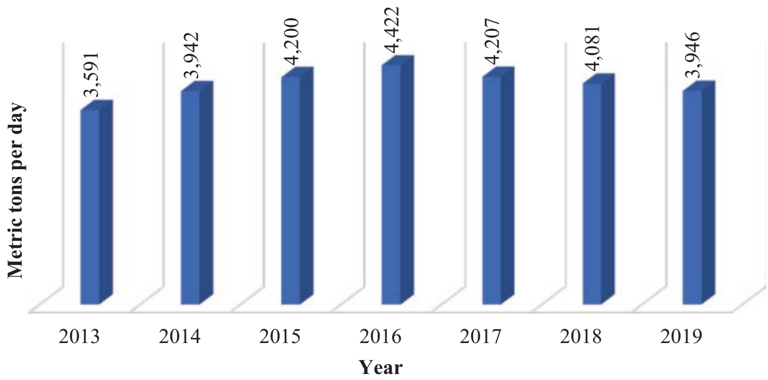


Fig. 1.12 Solid waste disposal to landfill in Hong Kong [4]

in the United States has risen significantly over the last 30 years. There were 600 million tons of construction and demolition waste in 2018, up from 135 million tons in 1990. With 143 million tons ending up in landfills, this represents a 300% increase [14].

In 2018, the amount of material debris produced during construction and demolition in the United States was broken down by material type in Fig. 1.11. Approximately 3.4 million tons of wood products were produced as waste during construction during this period.

In Hong Kong, nearly 4000 tons of total construction waste was disposed of daily in landfills in 2019 (Fig. 1.12). In Hong Kong, construction waste was generated at a lower rate than municipal solid waste.

The volume of non-hazardous solid C&D waste produced in the Abu Dhabi Emirate in 2019 was 3.7 million tons (Fig. 1.13).

1.4.2.3 Management

Many recyclable materials can be contained in construction waste. Crushed debris can be recycled in construction projects. Waste wood can also be recovered and recycled.

Waste management fees, based on the 'polluter pays' concept, will help reduce construction waste levels [29]. In 2019, a study method for optimizing the construction waste management fee in China was presented. China has a significant waste management issue, with most of its landfills located in urban areas. The study found that metal, wood, and masonry waste have separate waste management fees of \$9.30, \$5.92, and \$4.25, respectively. Waste management cost \$0.12 per m^2, or just under 11 ft^2, on average [30].

As for building design, renovation, and demolition in the European Union (EU), there is currently a heavy focus on recycling building materials and following a cradle-to-grave ethic. Depending on the political structure, their recommendations

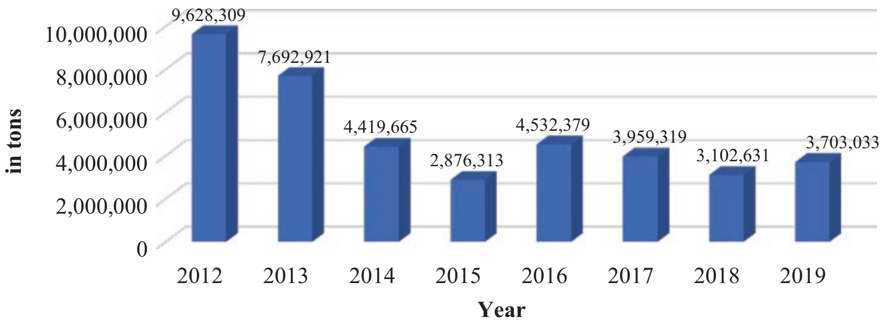


Fig. 1.13 Waste statistics in the Abu Dhabi Emirates [28]

are much easier and simpler at the regional or local level. In Austria, recent changes have been made in the processing of discarded wood products to be burned in the production of cement, reducing the carbon footprint of both products [31]. When issuing demolition and construction permits, the EU urges local governments to ensure that a high-quality waste management strategy is adopted, and they stress the significance of post-demolition follow-ups to assure that the established plans are followed. They also propose using taxes to reduce landfills' economic benefit, resulting in a situation where recycling becomes a financially viable option.

The landfill tax has had the greatest impact in Belgium, Denmark, and Austria, which have all reduced landfill disposal by more than 30% since the tax was implemented. Denmark has lowered landfill use by over 80% and has a recycling rate exceeding 60%. All staff conducting builders or construction waste clearance in the United Kingdom are required by law to be employed by a CIS registered company [32]. However, waste generation in the United Kingdom continues to rise, though at a slower pace. Although the United States does not have a national landfill tax or payment, many states and local municipalities do receive taxes and fees on solid waste disposal [33].

In 2008, the Malaysian Construction Industry Development Board (CIDB) published Guidance on Construction Waste Management [34]. The following items should be included in the building and demolition waste definition and strategy:

(a) Priorities based on the Solid Waste Management Hierarchy, which is widely recognised globally (Fig. 1.14).
(b) The cradle-to-grave approach.
(c) Device that is accommodating to the community.

The Solid Waste Management Hierarchy definition, as shown in Fig. 1.14 (right), is globally recognized and prioritizes waste prevention, reduction, reuse, recycling, waste treatment, and disposal in order of priority. The SWM Hierarchy prioritizes 'Waste Minimization' and the 3Rs: 'Reduce, Reuse, Recycle', with 'Treatment' (including Composting and Thermal Treatment) and 'Disposal', which involves landfilling, receiving the lowest priority.

Fig. 1.14 Solid waste management hierarchy

(a) *Waste Minimization/Reduction*

Waste reduction activities can save money by lowering material prices and lowering disposal costs. A systematic approach to waste minimization/reduction is recommended, which involves the contractual, construction, and site operation stages.

(b) *Reuse*

As much as possible, materials that can be reused on-site should be identified. Some of the most reused items include door sets, faucets and plumbing, fencing, plywood and chipboard, shelving and racking, siding and shutters, gutters, roof tiles, etc.

(c) *Recycle*

Recycling building materials reduce recycling costs, which saves money. It helps to keep construction sites cleaner and safer by reducing waste going to the landfill.

Waste recycling can be done in three ways:

Separation of sources: For each form of waste, several boxes are used. It does, however, take up more room and necessitates close supervision.

Commingled recycling: Recycling that is blended together. All is sorted off-site by the hauler. Commingled recycling takes up the least amount of storage room and is the best choice for sites with limited space.

Hybrid recycling: This recycling method incorporates site isolation and mixed recycling. One box for wood, one for concrete, and one for non-recyclable waste, for example. Hybrid recycling combines the benefits of both methods. It seeks the best balance between the weight and sorting effort. By operating in stages, the total number of boxes can be decreased. It decreases the amount of work for sorting haulers, reducing hauling fees.

Table 1.8 Some of the waste identification which could be done on-site

Types of wastes	Status of recyclables
Concrete	Recyclable
Bricks	Reusable
Plasterboards	Recyclable
Paint	Reusable
Timber	Recyclable/reusable
Pipework	Recyclable
Packaging	May be used for landscaping

(d) *Waste Minimization Plan*

Rather than modern technology, waste minimization needs a shift in mindset and common sense. Sometimes, waste minimization options are free to incorporate and offer immediate benefits with little or no effort.

(i) *Identifying and Exploration of Waste Minimization Opportunities*

Table 1.8 summarizes the steps involved in finding waste reduction opportunities

(ii) *Implementation of the Waste Management Plan*

(a) To the greatest degree possible, recyclable materials are separated from waste materials by form.
(b) Have clearly labelled containers for recyclable materials by form. Non-recyclable content does not make up more than 10% of the container's volume. If the 10% cap is surpassed, include other storage options for recyclable materials before they are removed from the project site.
(c) Separation of inert and non-inert materials for site formation and reclamation.
(d) Higher-grade usage, such as an inert waste road sub-base, is also possible if the necessary standards are met.

(iii) *Disposal/Recycling Services*

Contractors must ensure that their waste is disposed of at locations that have been approved by the local government. The Local Authorities closest to the project site will be given a list of permitted construction waste disposal sites. Contractors can sell recyclable products to local recyclers.

(iv) *Disposal/Recycling Services*

Contractors must ensure that their waste is disposed of at locations that have been approved by the local government. Contractors can sell recyclable products to local recyclers.

(v) *Implementation as a Whole*

It is necessary to create an organizational chart with responsibilities. A designated on-site waste manager (also known as a Safety, Health and Environment – SHE manager or a site manager) must be named. The following are his/her responsibilities:

1. Supervising the disposal of construction waste.
2. Managing campaigns aimed at reducing waste.
3. Coordination of other employees' operations.
4. Numerous services, such as employee awareness programmes, training programmes, and safety and health events, are carried out.

Staff awareness and training programmes are needed to gain their commitment. All levels of workers should be involved in awareness and communication activities. Furthermore, all employees must be briefed on the safety and health aspects of all construction activities, especially those involving waste management. Construction waste handling, segregation, and transportation procedures must provide safety and health precautions. Clients, consultants, and contractors will also help to reduce waste during the contractual stage of a project. The form of contract should be agreed upon by both parties. They should also notice the materials used, the project's team and workforce, the building methods and techniques, and any possible waste sources. Finally, content and waste audits should be conducted in order to find areas where future projects can change.

1.4.3 Electronic Waste (E-waste)

1.4.3.1 Definition

The acronym 'E-waste' stands for 'electronic and electrical waste'. Almost any household or commercial object with circuitry or electrical components falls into this category. It describes electrical or electronic devices or broken, non-working or old/obsolete electric and electronic appliances such as PC, TV, washing machine, air conditioner, and refrigerator.

1.4.3.2 Categories

The most common E-waste categories are as follows:

1. Temperature exchange equipment: Cooling and freezing equipment is more often termed as cooling and freezing equipment. Refrigerators, air conditioners, freezers, and heat pumps are examples of typical appliances.
2. Lamps: Typical equipment includes fluorescent lamps, high-intensity discharge lamps, and LED lamps.

3. Screens and monitors: Common equipment includes laptops, televisions, monitors, notebooks, and tablets.
4. Large equipment: Typical equipment includes washing machines, dishwashing machines, clothes dryers, electric stoves, large printing machines, copying equipment, and photovoltaic panels.
5. Small equipment: Vacuum cleaners, microwaves, ventilation machines, toasters, electric kettles, electric shavers, scales, calculators, radios, video cameras, electrical and electronic toys, small electrical and electronic tools, small medical devices, and small monitoring and control instruments are examples of typical equipment.
6. Small IT and telecommunication equipment: Mobile phones, GPS systems, pocket calculators, routers, personal computers, printers, and telephones are examples of popular equipment.

1.4.3.3 Impacts

Because of the exponential growth in demand for electrical and electronic devices, as well as the disposal after use, e-waste is becoming a global concern. If not properly treated, discarded electronic waste can pose a health and environmental risk.

Every part of our lives is increasingly entwined with technology. Semiconductors and sensors are now standard in a wide range of items that previously lacked them, resulting in smart homes, wearable watches, Internet TVs, and much more. To make it worse, the product lifespans are decreasing. When the batteries run out, several items will be discarded and replaced with new ones.

In developed countries, informal e-waste production may have negative health and environmental implications. There are some of the most significant factors for properly treating and recycling household e-waste:

1. Mercury, brominated flame retardants (BFR), and chlorofluorocarbons (CFCs), or hydrochlorofluorocarbons (HCFCs) are all harmful additives or hazardous substances found in e-waste. If e-waste is not adequately handled and is merely tossed out with the trash, potentially ending up in a landfill, both human health and the environment are jeopardized. The growing amount of e-waste, low collection rates, and non-environmentally sound disposal and treatment of this waste stream pose serious environmental and human health risks. Annually, 50 tons of mercury and 71 kilotons of BFR plastics are discovered in undocumented e-waste flows around the world, which is mainly released into the atmosphere and has an effect on the health of those exposed.
2. E-waste disposal that isn't handled properly leads to global warming. CFC (Freon) gases, which have a high global warming potential and lead to ozone depletion, are used in refrigerators and air conditioners. Increased UV radiation hitting the Earth's surface and skin cancers will result from ozone depletion. If e-waste products are not recycled, they will not be able to replace primary raw materials and hence will not be able to offset greenhouse gas emissions from the

production and refinement of primary raw materials. Finally, some of the refrigerants used in temperature exchange equipment are greenhouse gases. A total of 98 Mt of CO_2 equivalents were released into the environment as a result of poorly managed discarded refrigerators and air conditioners. In 2019, this represented around 0.3% of global energy-related emissions (IEA).

3. E-waste contains a plethora of hazardous materials that damage both humans and animals, as well as the environment. If e-waste is not adequately handled and is merely tossed out with the trash, potentially ending up in a landfill, both human health and the environment are jeopardized. E-waste contains a plethora of hazardous materials that damage both humans and animals, as well as the environment.
4. Other toxic components also present in e-waste:
   (a) Lead and cadmium are present in printed circuit boards (PCBs), which are used in a number of electronic appliances (cause brain damage, cancer, etc.).
   (b) Mercury has the potential to damage the brain and nervous system.
   (c) Lead has the potential to harm the brain and impair the normal processes of water and soil systems.
   (d) Brominated flame retardants (BFR): Under some conditions, brominated dioxins and furans, which are carcinogens, will recombine with un-oxidized carbon in smelter emissions.
   (e) Beryllium: Beryllium or beryllium-containing dust, mist, or fume inhaled by susceptible people may cause a chronic lung disease called berylliosis, and beryllium is a probable human carcinogen.
   (f) Hazardous chemical additives (such as phthalates) can leach from polyvinyl chloride (PVC) parts of electronic goods when they are discarded.
   (g) Arsenic is known to cause carcinogen in the skin, lungs, bladder, liver, and kidneys, with evidence of lung cancer. Death, inhibition of growth, photosynthesis, and reproduction, as well as behavioural effects of a particular flora/fauna organism, are all potential effects of arsenic on the environment.

1.4.3.4 Quantity

The amount of e-waste generated is increasing, and the types of e-waste are becoming more diverse. Since global market demand continues to rise, e-waste is among the strongest-growth sources of waste. Global e-waste production reached 53.6 million metric tons in 2019. It is expected to keep growing over the next decade. Global e-waste generation is expected to reach nearly 80 million metric tons by 2030, according to estimates. Asia is the continent with the most e-waste, with China producing the majority of it [35] (Fig. 1.15).

Various figures on e-waste in the world have been published by Forti et al. (2020) (Fig. 1.16). They discovered that the planet produced a staggering 53.6 Mt of e-waste in 2019, averaging 7.3 kg per capita. Since 2014, global e-waste generation has risen by 9.2 Mt, and is predicted to rise to 74.7 Mt by 2030, nearly twice in just

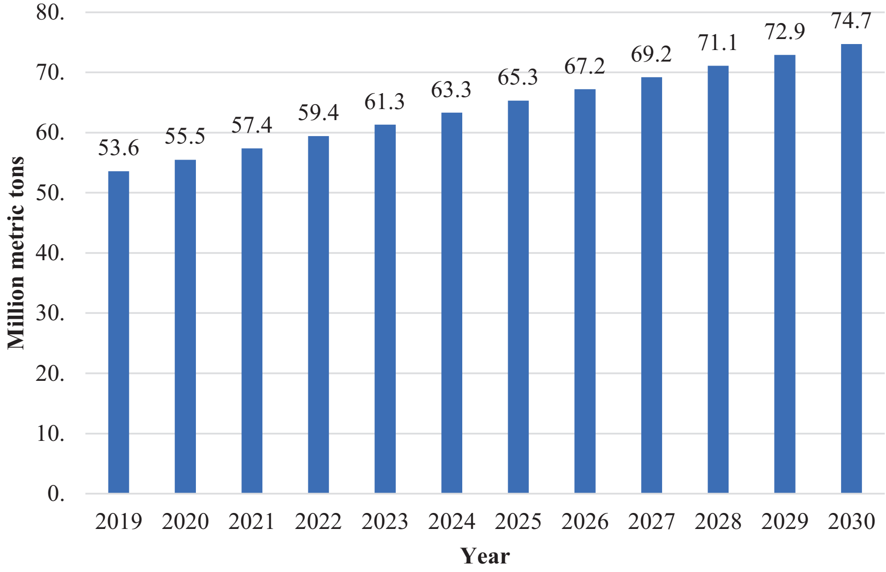


Fig. 1.15 Projected global electronic waste generation from 2019 to 2030 (in a million metric tons) [35]

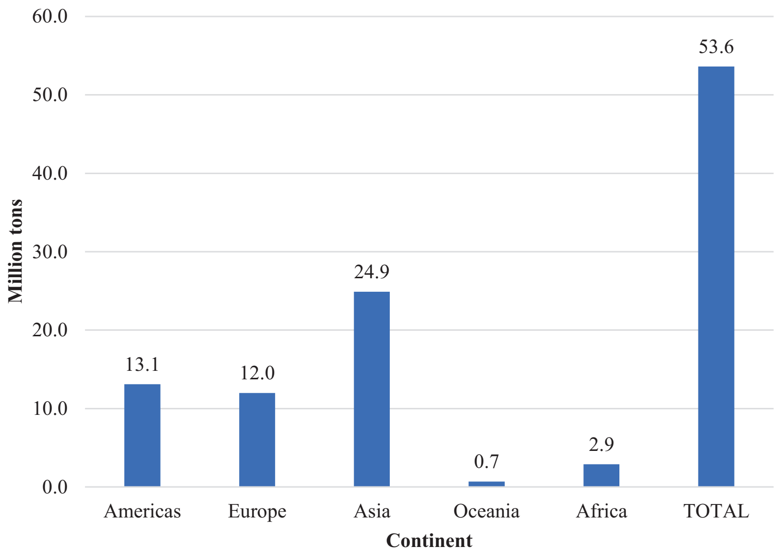


Fig. 1.16 E-waste generation worldwide in 2019 [35]

16 years. Higher electrical and electronic equipment (EEE) usage rates, short life cycles, and limited repair options are causing the increasing amount of e-waste. Asia produced the most e-waste in 2019, with 24.9 million tons, succeeded by the

Table 1.9 E-waste generation in ASEAN countries in 2014 [9]

No	Country	Kilogram/inhabitant	Annual amount (metric kilotons)
1	Brunei Darussalam	18.1	7
2	Cambodia	1	16
3	Indonesia	3	745
4	Lao PDR	1.2	8
5	Malaysia	7.6	232
6	Myanmar	0.4	29
7	Philippines	1.3	127
8	Singapore	19.6	110
9	Thailand	6.4	419
10	Vietnam	1.3	116

Americas (13.1 million tons) and Europe (12 million tons), with Africa and Oceania producing 2.9 million tons and 0.7 million tons, respectively. With 16.2 kg per capita, Europe ranked first in the world in terms of e-waste production. Oceania came in second (16.1 kg per capita), followed by the Americas (13.3 kg per capita), with Asia and Africa coming in third and fourth, respectively, with 5.6 and 2.5 kg per capita. They also reported that global e-waste generation is expected to hit nearly 80 million metric tons by 2030, according to estimates. Asia is the continent with the most e-waste, with China producing the majority of it. In 2019, formal reported collection and recycling totalled 9.3 Mt, accounting for 17.4% of total E-waste produced. Since 2014, it has risen by 1.8 Mt, or approximately 0.4 Mt per year (Table 1.9).

1.4.3.5 E-waste Recycling

E-waste composes a wide range of recyclable metals and materials. E-waste may be used as a resource. The Tokyo Organising Committee of the Olympic and Paralympic Games, for example, has launched the ‘Tokyo 2020 medal initiative’, which aims to create medals for the games out of recycled metals recovered from small waste electronic devices, such as discarded cell phones.

However, significant quantities of e-waste are also not being recycled properly. They end up in areas where there aren’t yet any proper recycling facilities. Many countries, on the contrary, have recognized the importance of properly recycling e-waste and are working to introduce long-term solutions.

Both formally and informally, e-waste recycling can be carried out. Disassembling the electronics, sorting, and categorizing the contents by material, and cleaning them is all part of proper or structured e-waste recycling. After that, the items are mechanically shredded in preparation for further sorting using advanced separation technologies.

Based on Cho [36], developed countries shipped nearly 23% of their e-waste yearly to developing countries. This is still ongoing, although the European Union and 186 countries have ratified the Basel Convention, which seeks to reduce hazardous waste movement from developed to developing countries. The Restriction of Hazardous Substances Directive of the European Union, on the other hand, corresponds to the whole EU market and thus has the power to set better standards for all electronic goods sold in the EU. Its regulations requiring manufacturers to contribute to the cost of recycling have caused a 35% e-waste recycling rate, which is higher than the United States.

1.4.3.6 What Can We Do About E-waste

Some of the 'green options' on e-waste disposal are as follows:

(i) *Designing Better Products*

Electronics manufacturers are encouraged to produce goods that are more durable, secure, repairable, and recyclable. Above all, this leads to using lesser quantity of toxic materials. This could be implemented by applying a cleaner production system that supports a proper Environmental Management System (EMS) – ISO14000 system in the company. A political will and commitment from the top are necessary to materialize this.

(ii) *Repair*

It is also important to repair and reuse faulty devices.

(iii) *Extended Producer Responsibility*

Extended supplier liability mandates that manufacturers be accountable for the disposal and management of their goods after the end of their useful lives. The concept behind the life cycle or cradle-to-grave theory is to recycle waste materials and use them to create new items. This option requires appropriate in place policy and probably legislation by the authority.

(iv) *Facilitate Convenient Recycling*

A proper drop-off recycling centre will facilitate user to send e-waste for recycling. On top of that, a proper roadmap should be structured so that the disposed of items are properly collected and processed. In most situations, processing and transportation are the beginning steps in the e-waste recycling flow. Recycling companies set up collection bins or electronic take-back booths in strategic areas and shifted the collected e-waste to recycling facilities. Materials in the e-waste stream are processed and separated into renewable goods that can be used to produce new items after being collected and transported to recycling facilities. The basis of electronics recycling is effective content separation. After that, the e-waste is shredded into small bits for further processing. The iron and steel are then separated from the waste stream on the conveyor by a strong overhead magnet, which is then ready for sale as recycled steel. Aluminium, copper, and circuit boards are separated from the content stream by mechanical processing. Glass and plastics can be separated using water separation technology. The separated materials are then sold as functional raw materials for the manufacture of new electronics or other items after completion of the shredding, sorting, and separation processes.

1.4.4 Radioactive Waste

1.4.4.1 Definition and Sources

Radioactive waste is a substance that has been contaminated with radionuclides or contains radionuclides and is no longer usable. Radionuclides are volatile atoms of a given element that spontaneously decay or disintegrate, releasing energy in the form of radiation.

Radiation affects all on the planet. Radiation at levels higher than normal background radiation, on the other hand, can be dangerous. High levels of radiation, such as that emitted from high-level nuclear waste, can also kill you. Based on the duration of exposure, the amount of radiation, and the decay process, radiation can cause cancer, birth defects, and other anomalies. For thousands of years, high-level radioactive waste from nuclear plants may be dangerous.

Military weapons production and testing, mining, electrical power generation, medical diagnosis and treatment, consumer product development, manufacturing, and treatment, biological and chemical research, and other industrial uses have all developed nuclear waste. The front-end source is from the front end of the nuclear fuel cycle and is usually alpha-emitting waste from the extraction of uranium. It often contains radium and its decay products. Isotopes produced in nuclear reactors make up the back end of the nuclear fuel cycle. These are mainly spent fuel rods, which contain fission products that emit beta and gamma radiation. Beta particle and gamma ray emitters are common in radioactive medical waste. Many of these can be disposed of by allowing them to decompose for a brief period of time before discarding them as daily garbage. Y-90 is used to treat lymphoma (2.7 days), I-131 is used to treat thyroid cancer (8.0 days), Sr-89 is used to treat bone cancer (52 days), Ir-192 is used for brachytherapy (74 days), and Co-60 and Cs-137 are used for brachytherapy and external radiotherapy (5.3 years and 30 years respectively). Alpha, beta, neutron, and gamma emitters can be found in industrial waste. Radiography uses gamma emitters, while neutron emitting sources are used in a variety of applications.

1.4.4.2 Form and Half-Life

The physical and chemical characteristics of radioactive waste can differ greatly. It may be a solid, a liquid, a gas, or even a mixture of the three, such as sludge. Water, dirt, paper, plastic, metal, ash, glass, ceramic, or a combination of several physical types can all be contained in nuclear waste. Low-level waste (LLW), intermediate-level waste (ILW), and high-level waste (HLW) are the three types of nuclear waste, based on the level of radioactivity and the period of time it remains hazardous. Waste can be radioactive for seconds, minutes, or even millions of years, depending on the radionuclides it contains.

A half-life is a duration it takes for a given amount of radioactive material to degrade to half its original value. A radionuclide's half-life can range from fractions of a second to millions of years. Sodium-26 (half-life: 1.07 s), hydrogen-3 (half-life: 12.3 years), carbon-14 (half-life: 5730 years), and uranium-238 are several examples of radionuclides with a variety of half-lives (half-life of 4.47 billion years). A radionuclide's decay process is the mechanism by which it releases excess energy spontaneously. Alpha, beta, and gamma emission are typical pathways for radioactive decay. Alpha decay is a mechanism in which excess energy is released by the ejection of two neutrons and two protons from the nucleus of heavy atoms such as uranium-238 and thorium-234. The ejection of a beta particle, which is the same as an electron, from the nucleus of an excited atom is known as beta decay. Strontium-90 is an example of a beta-emitter commonly found in radioactive waste. The nucleus of an atom is always in an excited state after an alpha or beta decay and still has excess energy. Instead of releasing energy through alpha or beta decay, energy is lost through gamma emission, which is a pulse of electromagnetic radiation emitted from an atom's nucleus.

Figure 1.17 [37] shows the amount of radioactive waste generated in France from 2016 to 2040, broken down by waste type and measured in cubic metres. According to estimates, there will be 6.9 million cubic metres of high-level waste in 2040. Figure 1.18 [37] depicts the economic sector's share of radioactive waste volume produced in France in 2018. The nuclear industry accounted for approximately 60% of France's nuclear waste in that year.

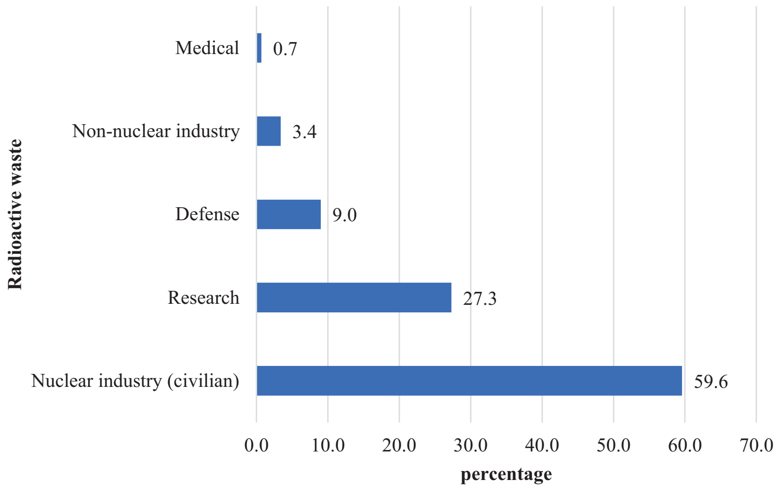


Fig. 1.17 The share of radioactive waste volume generated in France in 2018, by economic sector [37]

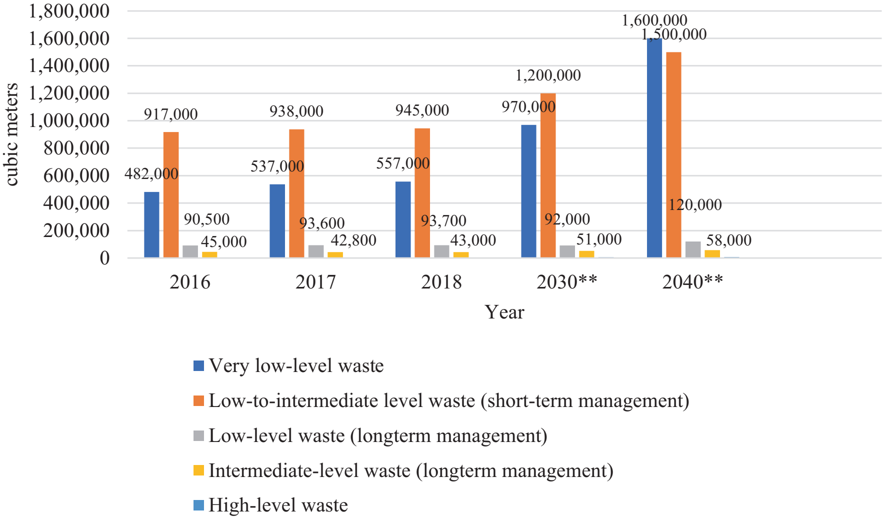


Fig. 1.18 The projected volume of radioactive waste produced in France from 2016 to 2040 [37]

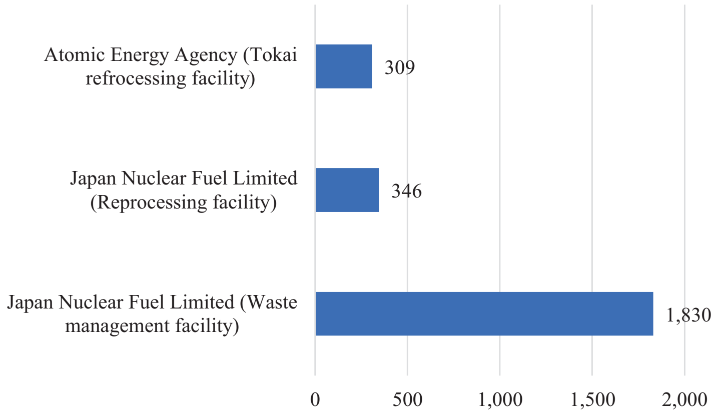


Fig. 1.19 Amount of high-level radioactive waste stored in Japan in 2019 by the company(in units) [38]

Figure 1.19 shows the volume of high-level radioactive waste deposited in Japan in 2019 by the organization (in units). It reveals that Japan Nuclear Fuel Limited's waste treatment facility has the most high-level radioactive waste [38].

1.4.4.3 Radioactive Waste Management

(i) *Introduction*

Possession, transportation, handling, storage, treatment, and final disposal of radioactive waste are all part of radioactive waste management, which aims to protect people and the environment. Human exposure to high-level radioactive waste can be dangerous, even fatal, if treated improperly.

The method of transport, the packaging required, and the labelling required to allow for the shipping of particular waste are all determined by the classification and physical size of radioactive waste. For nuclear waste, there are international transportation standards as well as more stringent legislation in individual countries. Only if the radionuclides present in the waste are directly inhaled or swallowed will certain radioactive wastes, such as some forms of transuranic waste, cause biological effects in humans. Humans can manage most low-level nuclear wastes without causing any noticeable biological effects.

(ii) *Commonly Accepted Management and Disposal Options*

The activities required for properly managing and disposing of radioactive waste can be divided into four categories, that is, reducing the amount of waste generated, conditioning and packaging to allow for safe handling and transportation, interim storage, and final disposal.

Since the radioactivity of the wastes decays over time, there is a strong incentive to store high-level waste for around 50 years before disposing of it. Low-level waste disposal is simple and can be done almost anywhere in a safe manner. Used gasoline, on the other hand, is usually stored underwater for at least 5 years and then in dry storage. The best option for the final disposal of the most radioactive waste generated is deep geological disposal, according to most experts. Options and examples of radioactive waste disposal are presented in Table 1.10 [39].

The bulk of low-level radioactive waste (LLW) is usually sent to land-based disposal for long-term management immediately after packaging. This means that a suitable disposal method has been developed and is being introduced around the world for the vast majority (90% by volume) of all waste forms generated by nuclear technologies.

The first step in storing used fuel classified as high-level radioactive waste (HLW) is to allow radioactivity and heat to decay, making handling much safer. Used fuel may be deposited in ponds or dry casks at reactor sites or centrally.

1.4.5 Litter

Litter is made up of man-made waste materials like paper cups, aluminium cans, cardboard boxes, fast food wrappers, or plastic bottles, and cigarette butts that have been improperly disposed of. It has a human impact on the environment and continues to be a significant environmental concern in many countries. Litter will stay visible for a long time before biodegrading, with certain products made of condensed glass, styrofoam, or plastic potentially staying in the atmosphere for years. Litter can travel long distances and end up in the world's oceans. Litter may have an

Table 1.10 Options and examples of radioactive waste disposal [39]

Option	Types of waste	Examples
Near-surface disposal: At ground level, or in caverns hundreds of metres below ground level	LLW or short-lived ILW	Many nations, including Finland, France, Japan, the Czech Republic, the Netherlands, Sweden, the United Kingdom, Spain, and the United States, have adopted it for LLW
		For LLW and short-lived ILW, it is used in Sweden and Finland
Deep geological disposal: Mined repositories are located between 250 and 1000 metres deep, while boreholes are located between 2000 and 5000 metres deep	Long-lived ILW and HLW (including used fuel)	The majority of countries have looked into deep geological disposal, and it is now a strategy
		It is used in the United States for transuranic waste that is related to protection
		France and Sweden were chosen as preferred locations
		Finland and the United States of America
		The collection of geological repository sites has begun in Canada and the United Kingdom

adverse effect on one's quality of life. Litter has a significant visual effect. Rainwater fills open containers such as paper cups, cardboard food packages, plastic drink bottles, and aluminium drinks cans, offering mosquito breeding grounds. Furthermore, if a spark or lightning flash hits litter, such as a paper bag or cardboard box, it may cause a fire.

Plastic/polystyrene fragments were the most typical form of litter found on British beaches (Fig. 1.20). This was significantly more than the second-most common form of litter, cigarette stubs, with 143 pieces per 100 metres of the beach [40].

Litter can trap or poison animals in their natural habitats. Cigarette butts and filters pose a risk to wildlife, having been discovered in the stomachs of fish, whales, and birds that mistakenly ate them for food. Animals may also get stuck in the garbage, causing serious pain. The plastic used to keep soda cans together, for example, can wrap around animals' necks and suffocate them as they grow. Broken glass lacerating the paws of dogs, cats, and other small mammals is another example of how litter can affect animals.

Litter is a major environmental issue faced by many countries in the world. Despite the fact that developing countries lack the resources to address the problem, developed-world market economies are capable of generating more litter per capita due to higher disposable product consumption.

It is preferable to prevent rather than cure. The most important thing is awareness. Many organizations exist with the goal of increasing awareness and implementing programmes, such as clean-up activities. World Cleanup Day is a global initiative. Specific litter movements are exemplified by TrashTag and Plogging. To fix the issue, some countries and local governments have enacted legislation.

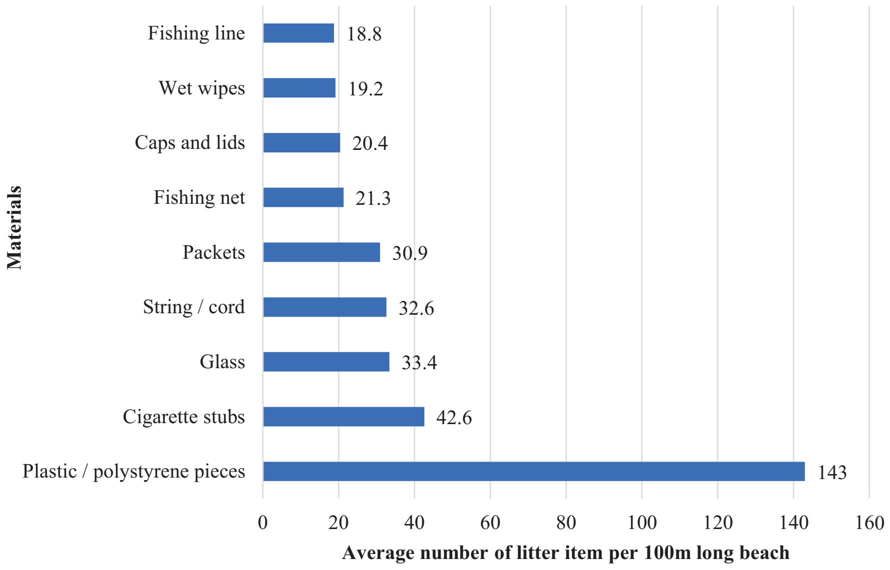


Fig. 1.20 The typical forms of litter found per 100 metres of beach in the United Kingdom (UK) in 2019 [40]

On-the-spot fines for individuals imposed by authorized officers in public or on public transportation, as well as littering from a car, are examples of actions that result in fines. Litter traps may be used to catch litter before it enters rivers from storm drains. Litter traps, on the other hand, are only suitable for large or floating litter and must be managed. Volunteers clean up trash and dispose of it, either individually or with the help of groups. Clean-up activities are often held in which participants search a region in a line to assure that no litter is missed. Litter clean-up activities can be promoted by organizations, as well as separate advertising campaigns to discourage littering. Local governments can also have appropriate municipal waste containers or street bins to be used as a safe location for litter disposal and collection.

1.4.6 Scrap Tyre

1.4.6.1 Introduction

Tyre recycling, also known as rubber recycling, is the method of repurposing waste tyres that have become unfit for application on vehicles due to wear or irreparable damage. Due to the large volume generated and their non-biodegradable nature, these tyres are a difficult source of waste and can take up valuable landfill space. Despite the fact that many junked tyres are burned haphazardly in open-air dumps, this activity should come to an end with the implementation of stricter air pollution regulations. Scrap tyres burn so hotly that they melt the grates of traditional incinerators, so most cities avoid incinerating them. Even when special incinerators are designed, the majority amounts of particulates, sulphur and nitrogen oxides, as well as hydrocarbons, are released, causing air pollution. Tyres do not lend themselves well to landfill disposal due to their low bulk density and resilience to biodegradation; whole tyres resist compaction and burying and rise to the surface, posing other issues such as disease vector breeding grounds and fire hazards.

Vulcanized rubbers have a strongly crosslinked structure and chemical composition, which contains toxic components such as leachable heavy metals; recycling waste tyres pose major environmental concerns [41].

1.4.6.2 Quantity

In the United States alone, around 270 million discarded tyres are produced each year. This necessitates the development of simple, energy-efficient, and cost-effective methods for recycling waste tyres [42]. In 2018, approximately 72.4 million metric tons of scrap iron and steel were processed (Table 1.11), while nearly 783,000 metric tons of plastics (only PET bottles) were handled in this country [43].

Between 1994 and 2010, the European Union increased tyre recycling from 25% to nearly 95% of annual discards, with approximately half of the end-of-life tyres being used for oil, mainly in cement manufacturing [44].

1.4.6.3 Tyre Recycling

Tyres are poorly degradable waste materials. Various solutions to reuse discarded tyres have been implemented in the world. While waste reduction initiatives will not solve the tyre issue, they will help to reduce the number of discarded tyres. According to the US Tyre Manufacturers Association [9], 16% of waste tyres are still landfilled, and these tyres are difficult to degrade and can stay in the environment for a

Table 1.11 Volume of scrap processed by type in the US in 2018 [43]

Types of scrap	Volume (thousand metric tons)
Zinc	72
Plastics (PET bottles)	782.9
Lead	1349
Copper	1783
Aluminium	5462
Electronics	5500
Paper	47,800
Iron and steel	72,400
Tyres (in thousand tyres processed – absolute number)	116,000

long period duration. Retreading, incineration for energy recovery, pyrolysis to obtain gas and carbon black, and shredding to create small particles used as fillers in a wide range of matrices such as asphalt, concrete, and polymers account for 86% of scrap tyres recycled. These recycling practices not only contribute to environmental conservation but also to the economic development of a number of industries, including artificial reefs, flood prevention, breakwaters, floatation devices, athletic tracks, playground surfaces, rubberized composites, and many others [45]. Retreading, incineration, pyrolysis, and mixing are the most common methods for recycling waste tyres (composites).

Figure 1.21 illustrates the recycling rates of different items in the urban waste stream in the United States in 2018. In that year, the tyre recycling rate was about 40%.

(i) *Tyre Retreading*

Retread is a tyre remanufacturing process that replaces worn tread with new tread. It's achieved by removing the tread and replacing it with a new one using cold or hot processes. As opposed to making a new tyre, it retains about 90% of the rubber in spent tyres and saves about 20% on material costs. Retread should not be confused with remoulding, which is a higher-quality version. It was scarcely used for passenger vehicles as of 2008, owing to road discomfort, safety concerns, and the advent of cheaper tyre brands on the market.

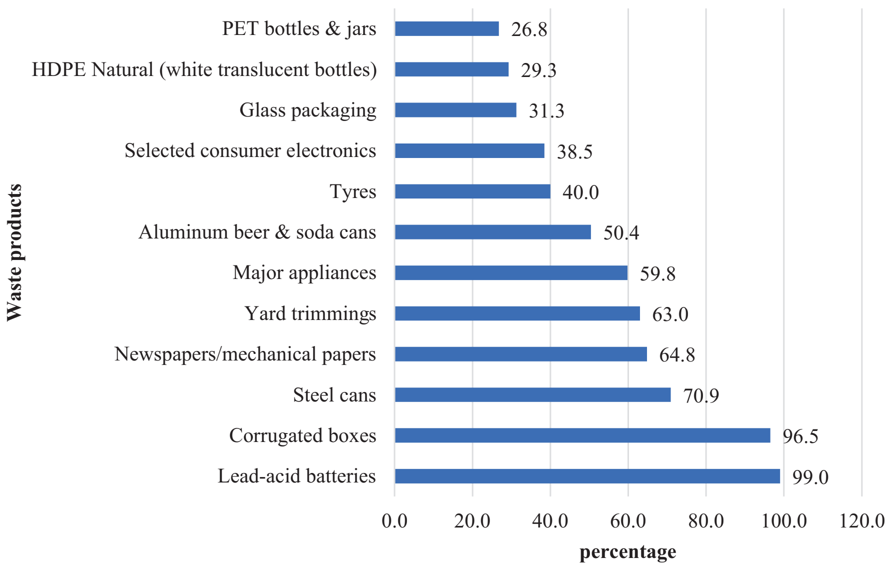


Fig. 1.21 In 2018, the United States' recycling and composting rates for a variety of items were calculated [3]

(ii) *Incineration*

Incineration of scrapped tyres may be used to generate steam. Waste tyres, which have a calorific value of 32.6 MJ/kg, are used to generate steam, electrical energy, pulp, paper, lime, and steel [46].

(iii) *Pyrolysis*

Tyre pyrolysis is a method of recycling tyres into useful materials for further manufacturing. Tyre pyrolysis, put simply, is the process of putting shredded tyre material into a big, sealed chamber and then heating the material up in the absence of oxygen. This will turn the waste tyre into useful goods like steel, carbon black, and tyre-derived fuel. The steel and carbon black can be used to make new tyres as well as a variety of other products. The tyre pyrolysis oil is used to produce energy for a variety of industries as a more environmentally sound alternative to many traditional combustion products. Cement plants often use this kind of fuel when it is available.

(iv) *Tyre-Derived Products*

Tyres may be repurposed in a variety of ways. New products made from waste tyres are beneficial than combustion or other low-multiplier output while also reducing waste and reducing pollution and emissions from recycling operations. Construction materials, artificial reefs, tyre-derived aggregate (TDA), ground and crumb rubber – also known as size-reduced rubber – can be used in both paving style projects and mouldable products are among the new waste-derived products. Rubber Modified Asphalt (RMA), Rubber Modified Concrete, and as a substitute for aggregate are examples of these forms of paving.

(v) *Alternative Fuel*

In cement production, used tyres are fed mid-kiln to a pair of long cement kilns. It is used as an alternative fuel in the production of Portland cement, a crucial component of concrete. Whole tyres are often inserted into cement kilns by rolling them into the upper end of a preheater kiln or dropping them through a slot in the middle of a long wet kiln. In any case, the high gas temperatures (1000–1200 °C) cause the tyre to burn almost immediately, completely, and smokelessly. Alternatively, tyres can be chopped into 5–10 mm chips and injected into a pre-calciner combustion chamber in this shape. Since cement production requires some iron, the iron content of steel-belted tyres is advantageous to the process [47].

1.4.7 Solid Waste from Air and Water Pollution Controls

Sulphur oxides and particulates are the most common air contaminants that can result in solid waste residues. The processing of solid waste residues is unaffected by other air contaminants. Because of the wide variety of substances released into receiving waters, determining crucial water contaminants capable of generating solid residues is more challenging.

Aside from power plants, non-ferrous smelting and processing, chemicals and allied products, paper and allied products, cement and dry products, steel, and hazardous wastes are all major industrial sectors that generate solid wastes from air and water pollution control. These industries, along with power plants, contributed roughly 90% of all solid wastes from air and water pollution control.

Large quantities of ash, as well as carbon dioxide and other gases, are emitted during coal combustion. Fly or flue ash is the fine particle ash that rises with the flue gases, while bottom ash is the heavier ash that does not rise; these two types of ash are referred to as coal ash. Also known as boiler slag, coal slag is a recycled product created by coal-burning plants. The slag is cooled by vitrification, which causes it to solidify and form sharp, angular granules of various sizes.

Mangli et al. [48] reported in their analysis that global coal ash output is expected to be about 600 million tons per year, with fly ash accounting for about 500 million tons [48]. Every day, a 500 MW thermal power plant emits around 500 metric tons of fly ash. By 2020, if fly ash is disposed of in ash ponds (usually in the form of slurry), the total land available for ash disposal would be about 82,200 ha, assuming a 0.6 ha per MW rate [49].

Despite recent developments in and increased use of renewable energy sources, coal-fired power plants still produce about 40% of the world's electricity. This figure is substantially higher in some nations, such as India, where it is about 70%, and South Africa, where it is over 90%. Large quantities of ash, as well as carbon dioxide and other gases, are produced during coal combustion. A fly or flue ash is a small particle of ash that rises with the flue gases, while bottom ash is harder ash that does not rise; these two types of ash are referred to collectively as coal ash [50].

APCr stands for air pollution control residues and is usually made up of ash, charcoal, and lime. It's hazardous waste that's actually being disposed of in a secured landfill or is being treated for non-hazardous disposals, such as washing or stabilization. According to government estimates from July 2015, about 300,000 tons of APCr are generated in the UK per year, though this figure is expected to rise dramatically in the year ahead as a major portion of domestic waste is handled in incinerator facilities. By 2020, this figure could reach 600,000 tons [51].

The average amount of sludge generated per capita per day was calculated to be 0.04 kg dry matter, corresponding to a 246 L per capita and day wastewater production rate [52]. This corresponds to a daily intake of 35 to 85 g dry solids per population equivalent (IWA, 2021; IWA, 2022) [53]. Between 2007 and 2013, China's total sludge generation rose by 13% annually, resulting in 6.25 million tons of dry solids produced in 2013. Sludge generation per capita in China is lesser than in developed countries [54].

Separation procedures, solidification/stabilization (S/S), and thermal methods are the three types of effective treatments for APC residues [55]. Fly ash was once freed into the atmosphere, but because of its potentially toxic impacts, it is now extracted from flue towers using electrostatic precipitators or other particle filtration equipment. After that, it can be thrown away or recycled into Portland cement.

Benefits of 'Bottom Ash' and 'Fly Ash' readily combine with calcium hydroxide to form required compounds in the cement manufacturing process, making it a less costly alternative to clay, sand, limestone, and gravel. Fly ash produces solid, long-lasting concrete that is chemically resistant. Bottom ash can also be utilized as a building material. As stated by the European Coal Combustion Products Association, bottom ash is used 46% of the time in manufacturing, while fly ash is used 43% of the time [50].

Electricity generated from sewage sludge digestion increased over the years in the United Kingdom, peaking at some 1.05 terawatt-hours in 2019. Between 2010 and 2019, figures increased by 352 gigawatt-hours [56]

1.5 Functional Elements of a Waste Management System

There is no overarching solution to waste management that can be extended to all waste sources; however, the implementation of a hierarchy ranking approach for solid waste management is the most adapted management strategies in many countries.

The management of this generated waste is a great challenge for the public and local authority. MSW management is an environmentally friendly method in managing waste, which consists of planning, administration, organization, generation, storage and collection, transportation, processing and recovery, and disposal methods that follow the waste management hierarchy (Fig. 1.14).

For example, open dumping and waste burning are common in the majority of ASEAN countries, according to UNEP [8]. Composting and anaerobic digestion of organic wastes, as well as the recovery of useful recyclables like paper, plastic, and metal, are common in ASEAN. The informal sector, on the other hand, is more responsible for recycling. Singapore, however, is an exception to the rest of ASEAN, as it has a sound and well-organized waste management system in place. Due to its limited land resources, Singapore chooses waste-to-energy (WTE) via incineration as its primary waste management choice.

1.5.1 Onsite Handling and Storage

Each country and area has its own approach to waste management. The unsafe handling of MSW can pollute water and soil, as well as have a significant effect on public health. In most cases, waste is deposited after it is produced at its source before being collected and transported to a disposal site.

The type of container, the location of the container, the effect on public health, and the waste disposal methods should all be taken into consideration when onsite storage of solid wastes. The capacities and types of containers used for on-site waste storage are determined by the characteristics of collected solid waste, the frequency of collection, and the container's usable capacity.

In several countries, there are two forms of waste storage: commingled waste storage and separated waste storage. Initial or mixed wastes are referred to as commingled waste. Commingled waste storage was the most common method, with 84% of households storing waste in this manner and the rest separating organic waste from other wastes. A collective bin has been set up for a group of houses or a particular neighbourhood. In general, the type of waste container chosen is determined by the area's primary operation. A waste bin or a wheelie is commonly used to collect waste directly from a residential home. Meanwhile, communal bins are given for low and medium-sized buildings, and residents may either pass their waste into the communal bins themselves or use the building maintenance personnel's services. In Malaysia, for example, spiral waste bins (SWB) are found in apartments and condominiums where large amounts of waste are produced. Due to its ability to compact waste, SWB allows for a higher storage volume [57]. This will result in a more hygienic and effective environment, but it will be costly to introduce. In Malaysia, these systems are used at Kuala Lumpur International Airport (KLIA), Complex, Kastam Kelana Jaya, and Kompleks Maju Junction [58]. Local governments or private companies typically have a rolled-on/rolled-off (RORO) bin, a 12 m^3 bin that can be rolled on and off the trailer in the industrial and wet market.

In Malaysia, three types of collection systems are used for waste segregated at source: kerbside collection using traditional and specially built vehicles, incidental kerbside collection by a voluntary agency, and residents transporting the separated waste to drop-off and recycling centres. As a result, people must use their own bins and separate their trash from the source. Containers of any kind, such as boxes and drums, may be used. However, recycling bins can be found in some suburban areas as well as many other public places to raise recycling awareness among the general public.

Some of the common bins being used are shown in Fig. 1.22.

1.5.2 Waste Collection

Waste collection is a step in the waste management process. For the preservation of public health, environmental quality, and safety, proper solid-waste collection is critical. It is the transportation of solid waste from its point of origin to a materials processing plant, transfer station, or landfill disposal site. As part of a municipal landfill reduction scheme, waste disposal also involves the kerbside collection of recyclable items that are legally not waste. The collection operation consumes roughly 50–70% of the total amount needed for solid waste management (collection, transport, processing, recycling, and disposal) [59]. In Malaysia, for example, solid waste management accounts for almost half of the local authority's (municipal) operating budget, with waste collection accounting for the other half.

Fig. 1.22 Some of the typical storage bins

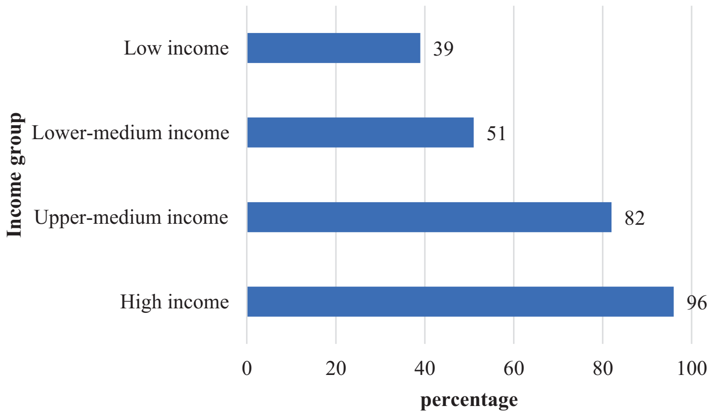


Fig. 1.23 Waste collection rates by income level (%) [8]

Waste collection is a significant part of waste management, but rates differ a lot depending on income levels, with upper middle- and high-income countries having an almost universal waste collection. In cities, low-income countries collect about

Fig. 1.24 Example of the house-to-house collection

48% of waste, but outside of cities, this percentage drops to just 26%. Sub-Saharan Africa collects about 44% of waste, while Europe and Central Asia, as well as North America, collect at least 90% of waste (Fig. 1.23) [8].

The collection system is influenced by the type and source of waste. For household waste, a door-to-door collection system is mostly adopted where household waste is removed from the home (Fig. 1.24). For areas not fully accessible to collection vehicles, a common bin is normally provided shared by many residents or streets. For a high rise building or flats, a communal bin is used, and the collection is normally done daily.

Commercial and non-hazardous waste collection is normally done primarily using dumpsters from a commercial bin. The recyclable material collection is adopted for the collection of recyclable materials separated at the source of generation.

The collection system also depends on various factors, which include but not limited to

- The served area
- Types and tonnage/volume of waste generated
- Presence or absence of waste recycling facility
- Types of waste treatment system – landfill, composting, anaerobic digester, incineration, etc.
- Economic constraints
- Types of the collection vehicle

Commercial and non-hazardous industrial waste is typically handled by a hauled container system or a stationary container system.

(i) A hauled container system is one in which a waste storage container is transported to a disposal site, drained, and then returned. Alternatively, the empty and loaded containers are usually swapped on-site by the truck.
(ii) A stationary container system is one in which waste storage containers remain at the point of generation after being emptied.

Waste disposal is a time-consuming task that accounts for almost three-quarters of the overall cost of solid waste management. While the job is often done by public employees, it is often more cost-effective for the municipality to contract out the collection services to private companies. Each collection vehicle is usually served by a driver and two to three collection staff. These are typically sealed, compacting trucks with capacities ranging from 10 to 30 cubic metres. The truck will come to a halt at each residence where the bin is stored (front or back of the street). This collection system's routing should be optimized to save time and fuel consumption. Compaction in the truck would be reduced to less than half of its total volume.

Choosing the best collection route is a difficult task, particularly in populated and dense cities. An optimal route is one that allows the most efficient use of labour and equipment, and selecting one necessitates computer calculations that account for all of the numerous design variables in a large and complicated network. Frequency of collection, haulage distance, service type, and environment are all variables. Collection of waste in rural areas can be particularly challenging due to low population densities and high unit costs.

Since food waste decomposes easily, refuse collection is usually performed at least once a week. In a hot climate, however, the collection is usually done three or four times per week. Commercial assets such as hypermarkets and wet markets have regular collections.

Many cities now have source separation and recycling systems, in which households and businesses separate recyclables from garbage and deposit them in separate bins for collection. Residents may also carry recyclables to drop-off centres in certain cities. The municipality usually assigns a dedication collection system to do the collection.

Fig. 1.25 Example of compactor truck

Fig. 1.26 Ro–ro bin

Fig. 1.27 Open truck

There are a few types of collection vehicles. The most common are as follows:

(i) Compactor truck (Fig. 1.25). It receives wastes from small (household) bins and medium (communal) bins.

(ii) Roll-on–roll-off (Ro–Ro) (Fig. 1.26). The trucks haul large bins (Ro–Ro bins) to disposal sites.

(iii) Open trucks (Fig. 1.27). Open trucks used to cart landscaping and grass, cutting wastes to landfill. A net is often fastened on top of the load to prevent waste from dropping. However, some private contractors still use open trucks to collect and transfer household wastes.

The waste collection could also be categories in terms of the primary and secondary system. These are detailed in Table 1.12 [60].

Table 1.12 Options for primary and secondary waste collection [60]

Vehicle	Comments
Primary	
Wheelbarrow	Recommended for waste collection from households located in narrow streets to a communal collection point. Required maintained street surface
Handcart	Stable for waste transfer in long distance, especially on the road with bad surfaces. It is recommended for the door-to-door waste collections in crowded areas
Cycle cart	Can move up to 3 m^3 of waste to a communal bin or a transfer station
Tractor	Higher costs than all other options; however, it recommended transferring a large volume of waste for long distances
Secondary	
Truck bin lifter	Suitable for collecting and transferring communal bins from residential and commercial areas
Enclosed light truck	Suitable for waste collection from narrower streets
Flatbed crane truck	It is recommended for waste collection from transfer stations, markets, and industrial areas
Compactor	Expensive method for waste collection and transfer. Not suitable for high-density wastes. It required high skills for maintenance. It is recommended for low-density waste with large volumes

1.5.3 Pneumatic Waste Conveyance System (PWCS)

The PWCS is an automated waste collection system that collects household waste via a vacuum-type underground pipe network and transports it to a sealed container through underground pipes. The waste is then collected on a daily basis by trucks for disposal. The storage of the entire waste is automated, which decreases manpower requirements while increasing efficiency. The PWCS (Fig. 1.28) decreases the environmental and sanitary problems that open refuse collection methods cause [61].

The PWCS scheme has many advantages. Some of them are as follows:

- The entire refuse collection process is automated.
- Manpower is limited, as is the need for manual labour.
- Improved working standards.
- Removes noxious odours produced by refuse chutes.
- Reduces spills during garbage collection, resulting in a more sanitary and safer climate.
- Pleasant to the atmosphere.
- Reduces the need for chute cleaning.
- Pest infestation is reduced.
- Waste decomposition is minimized.
- Encourages waste separation for recycling at the collection point.

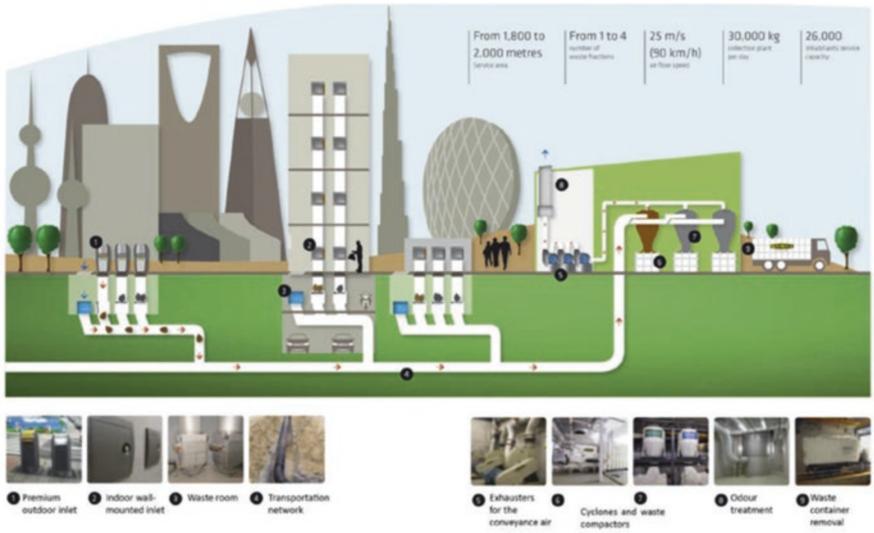


Fig. 1.28 Basic layout of a waste pneumatic collection system [62]. Reprinted from Chafer, M., Sole-Mauri, F., Sole, A., Boer, D., Cabeza, L.F. Life cycle assessment (LCA) of a pneumatic municipal waste collection system compared to traditional truck collection. Sensitivity study of the influence of the energy source, *Journal of Cleaner Production*, 231 (2019), 1122–1135, with permission from Elsevier

1.5.4 Transfer Station

If the waste's final destination is not close to where it was created, at least one transfer stations may be needed. A waste transfer is a method of decreasing the cost of managing recyclable waste while increasing the volume of recyclable waste. A transfer station is a central location where refuse from multiple collection vehicles is consolidated into a bigger vehicle, like a tractor trailer. The waste is then transported to a recycling or disposal plant, usually over long distances. Open-top trailers normally can transport up to 76 cubic metres (100 cubic yards) of non-compacted waste to a centralized processing or disposal facility [63]. Enclosed compactor trailers with ejector mechanisms are sometimes used. Multiple collection trucks dump directly into the transport vehicle at a direct discharge station. In a storage discharge station, trash is first drained into a storage pit or onto a platform, and then the solid waste is hoisted or pushed into the transport vehicle using machinery. Large transfer stations normally have the capacity to handle over 500 tons of garbage every day. If the waste's final destination is not close to where it was created, at least one transfer stations may be needed. A waste transfer is a method of decreasing the cost of managing recyclable waste while increasing the volume of recyclable waste.

There are a few options in the transferring activities of waste. The common transfer activities that take place at transfer stations are reloading (transferring from smaller truck to larger truck), compaction, or separation of the waste (Fig. 1.29) [63].

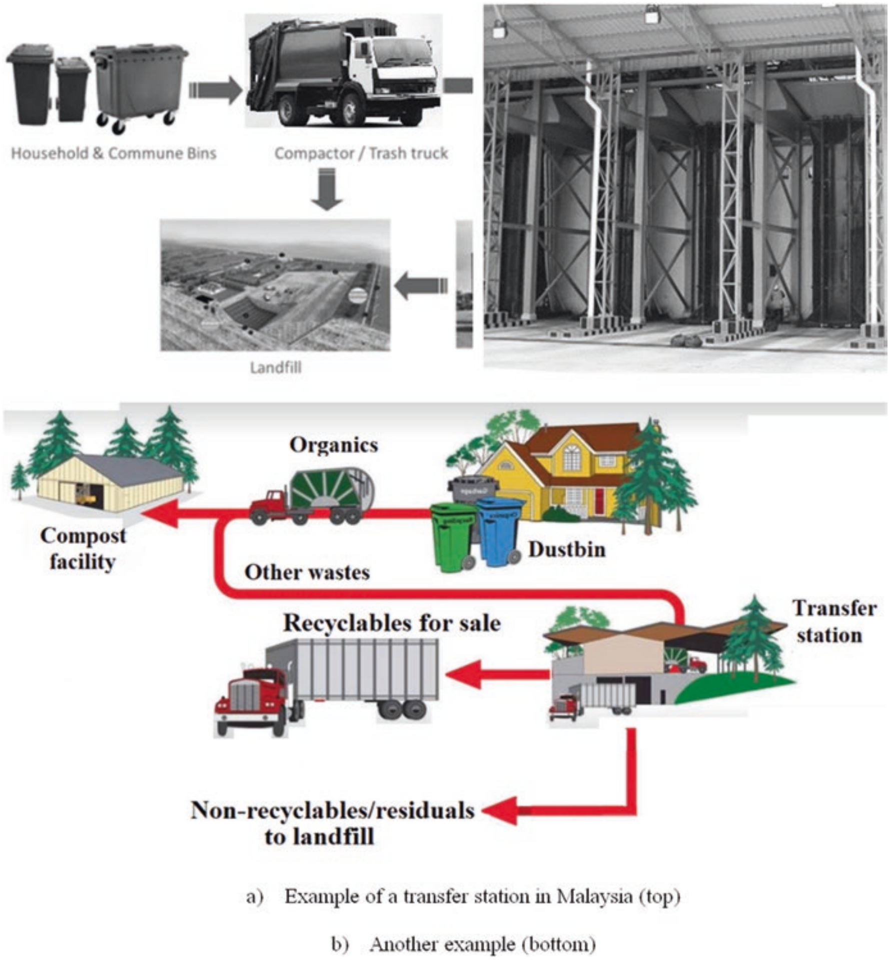


Fig. 1.29 A typical transfer station [63]. (**a**) Example of a transfer station in Malaysia (top). (**b**) Another example (bottom)

1.5.5 Waste Processing and Recovery

Solid waste management employs a variety of technologies. Recycling is the method of extracting the economic value of products and resources from waste that would otherwise be discarded. It basically refers to the gathering and processing of recycled materials into new types that can be used as raw materials for new goods. Although the word is most often associated with municipal waste, it may also refer to industrial or other types of waste. All of the processes, tools, technology, and facilities used to increase the performance of the other functional components, as well as the reuse of recycled materials and energy conversion from solid waste, are included in the functional aspect of recycling.

In order to recover recyclable materials from MSW, there are three specific methods that can be used:

- Separation at the source by the owner of the building, company, or organization. This is the most straightforward and efficient approach. Additional processing may or may not be needed.
- Collecting mixed recyclables and processing them at consolidated materials recovery facilities (MRFs).
- Mixed MSW collection with processing at mixed-waste processing or front-end processing facilities to extract recyclable products from the waste stream.

Recycling has two main advantages: It conserves natural resources and landfill space, thereby extending the life of landfills. As the process of recycling involves the collection and transport of materials requiring substantial amounts of energy and labour; it, therefore, creates more job opportunities. Recycling discourages the disposal of material that can either be reused or recycled into something useful, and it helps to provide a source of raw material that has monetary value. For example, the sale of aluminium, newspapers, cardboard, glass, plastic, and other recycled materials can potentially reduce a community's waste management costs. Inevitably, recycling practice, in a way, contribute to the conservation of natural resources. Recycling 1 ton of paper, for example, saves 17 mature trees, 7000 gallons of water, 3 cubic yards of landfill space, and 2 barrels of oil [58]. A proper materials recovery system will reduce the waste management operating cost by means of recyclables sell, energy-saving, and lower volume of waste disposal.

The rate of recycling varies widely across the world, depending on national waste management legislation. With a rate of 59%, Singapore and South Korea had one of the highest rates of urban solid waste recycling. Figures 1.30 [64] and 1.31 [3] depict MSW solid waste recycling rates worldwide in 2017 by region, as well as the number of materials recycled in the United States from 1960 to 2018. The amount of MSW recovery and recycled has risen since then, reaching 69 million tons in 2018 [3].

The bulk of waste processing and recycling takes place at a materials recovery facility (MRF) (Fig. 1.32) [3]. Figure 1.33 shows a statistic for the sum of materials collected from urban waste sources in the United States in 2018, based on material. Rubber and leather products were recovered from urban waste in the amount of 1.67 million metric tons this year [3].

It is a dedicated plant that accepts commingled products and separates and densifies them for sale to end-user manufacturers using a combination of machinery and/or manual labour. Mechanically, using variations in physical characteristics of the waste such as height, density, and magnetic properties, these are carried out. The size of the waste articles is decreased by shredding or pulverizing, resulting in a uniform mass of material. Hammer mills and rotary shredders are used to do this.

Various MSW constituents can be separated and recovered via recycling. The most common ones are paper, plastics (PET and HDPE), glass, aluminium, ferrous

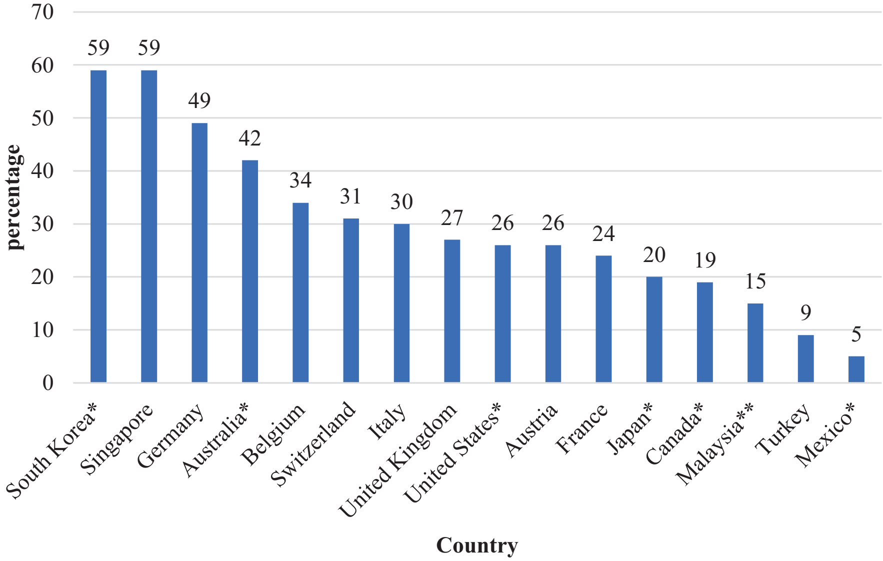


Fig. 1.30 Recycling rates of municipal solid waste in 2017 by country (**Estimated) [58]

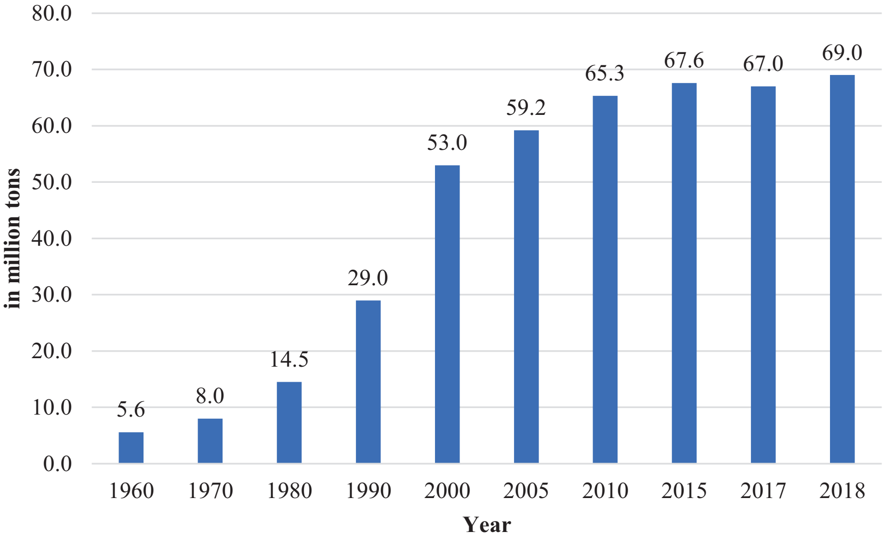


Fig. 1.31 The amount of materials recycled in municipal solid waste in the United States between 1960 and 2018 [3]

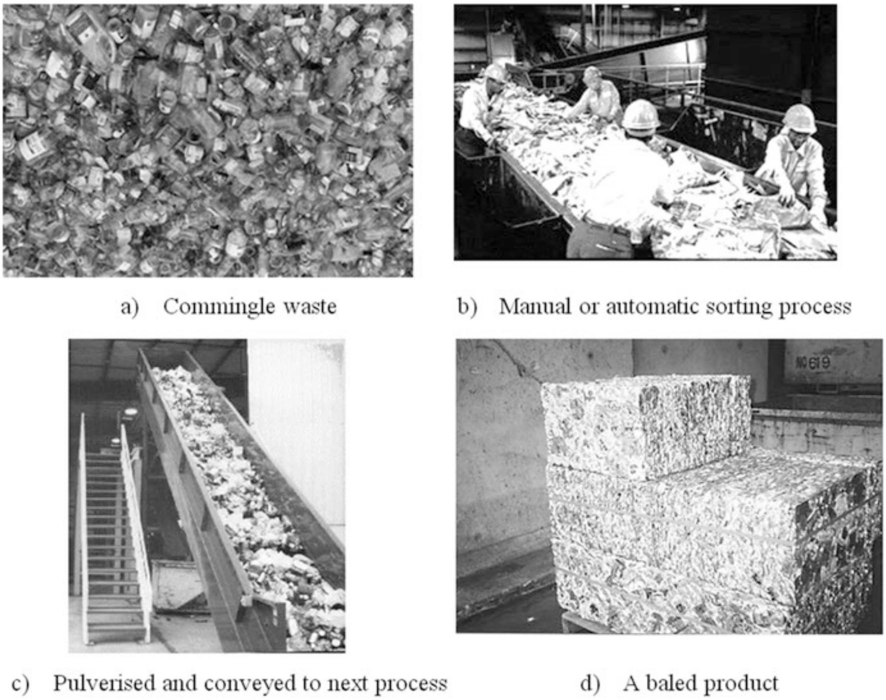


Fig. 1.32 An example of a typical MRF facility. (**a**) Commingle waste. (**b**) Manual or automatic sorting process. (**c**) Pulverised and conveyed to next process. (**d**) A baled product

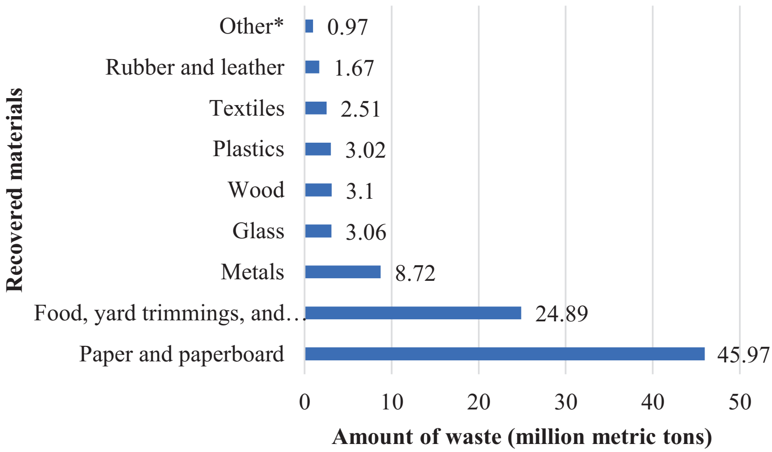


Fig. 1.33 The number of materials recovered from industrial waste in the United States in 2018, based on content [3]

metals, and non-ferrous metals. There are two categories of MRFs: clean and dirty. Clean MRFs manage the contents of commingled recycling bins that are mainly recyclable, while dirty MRFs handle solid waste that contains some salvageable recyclable materials (Table 1.13).

1.5.6 Composting

One of the solid waste treatment techniques is a composting process which has been practised since ancient times. The composting process converts the waste into organics that can be used for enhancing soil quality. In the conversion process, the normal microbes found in soil has been considered in addition to optimizing their carbon-cycling activities. In composting systems, the physical factors in the soil system, including temperature, moisture, and bulk density, are controlled internally.

There are several types of composting, as detailed in USEPA [66], as follows.

1.5.6.1 Basic Composting

Feedstock and nutrient balance, particle size, moisture content, oxygen flow, and temperature are the five key areas that must be 'regulated' during composting. It is important to maintain a proper balance of organic materials and oxygen flow. Grass clippings, food waste, and manure are examples of organic material that contain a lot of nitrogen. Dry leaves, wood chips, and branches are examples of 'brown' organic materials, which contain a lot of carbon but little nitrogen. Experimentation and persistence are needed to find the right nutrient mix. It's all part of the composting art and science. Smaller particles also help maintain optimum temperatures by producing a more homogeneous compost mixture and improving pile insulation. However, if the particles are too small, they can prevent air from freely flowing through the pile. To live, microorganisms in a compost pile need an adequate amount of moisture. Water is a crucial component in the compost pile because it aids in the transport of substances and makes nutrients in organic matter available to microbes. Moisture can be found in organic material in different quantities, but it can also be found in the form of rainfall or deliberate watering. Aerating the pile allows for quicker decomposition than in anaerobic environments. However, be careful not to provide too much oxygen, as this will dry out the pile and slow the composting process. Microorganisms need a specific temperature range to work properly. Temperatures that encourage rapid composting and kill pathogens and weed seeds are ideal. The temperature of the pile's centre will rise to at least 140 °F due to microbial activity. Anaerobic conditions (i.e., rotting) evolve if the temperature does not rise. The proper temperature can be achieved by regulating the previous four variables.

Table 1.13 The available technologies used for solid waste processing, treatment, and disposal [65]

Types of waste and technology available	The processing	Key issues
Paper	Paper recycling	High capital investment is required
	Waste to energy	No auxiliary fuel needed
		High capital investment is required
Plastic	Incineration	High calorific value, no auxiliary fuel needed
		Efficiency is high
		High capital cost
	Recycling	Expand landfill life span
		Needs to identify buyers
Construction waste	Reuse and recycling	Substitute for new products
		Non-recyclables/residuals sent to landfill
Organic and garden	Composting	Improves nutrient quality, thus destroying pathogens and acting as a soil conditioner
		Time-consuming and requiring a substantial amount of land
	Anaerobic digestion and methanation	Generates anaerobic/gaseous fuel
		Reduction in greenhouse gas emission
		Capital-intensive method
		Less effective for lower biodegradable
Inorganic	Sanitary landfills and landfill gas recovery	Cheaper if the land is available
		Potential for energy recovery of landfill gas
		May cause air and water pollution if not designed and maintained properly
		Land requirement is high
	Refuse-derived fuel (RDF) production	A burner made of RDF pellets
		Trained staff are needed
		A large initial capital expenditure is required
Chemical/hazardous	Recycling	Recycled into new products
		Skilled person required
	Incineration, waste to energy	Reduced air pollutants in modern design
		Involves high capital investment
		Requires good air pollution control systems
	Hazardous waste landfill	Secured landfill with extra pollution control
		High capital investment
		Expert requirement
Medical/hospital	Off-site	Proper handling and expert requirements
		Mainly incinerated

(continued)

Table 1.13 (continued)

Types of waste and technology available	The processing	Key issues
E-waste	Recycling	E-waste recycling centres must be devoted
		Electronic devices contain potentially dangerous materials, such as poisonous chemicals
Metal	Recycling	Metal recycling saves landfill space and requires a large initial investment
		Ample space is needed

1.5.6.2 On-Site Composting

Limited quantities of leftover food may be composted. Animal products and significant amounts of food scraps should not be composted on site. Changes in the weather and seasons will have little effect on on-site composting. As things change, such as when the rainy season begins, small adjustments can be made. Food scraps must be handled carefully to prevent odours or to attract unwanted insects or animals. Composting, in this manner, requires very little time and equipment.

1.5.6.3 Vermicomposting

This process employs worms to break down food waste into high-quality compost known as castings. Worm bins are simple to build and can also be purchased. A pound of mature worms (roughly 800–1000 worms) can consume up to half a pound of organic matter per day. The bins can be modified to suit the number of food scraps that will be used to produce castings. The time it takes to make functional castings is normally 3 to 4 months. You may use the castings as potting soil. Worm tea, another by-product of vermicomposting, is a high-quality liquid fertilizer for houseplants and gardens. Temperatures of 55 °F to 77 °F are ideal for vermicomposting. The bin should be put in the shade in humid, arid areas. Many of these issues can be avoided by vermicomposting indoors.

1.5.6.4 Aerated (Turned) Windrow Composting

This form is best suited to large volumes, such as those produced by entire communities and collected by local governments, as well as high-volume food-processing operations. It will create a significant amount of compost, which could be sold as a finished product. This method of composting entails sorting organic waste into rows of long piles known as ‘windrows’ and aerating them on a regular basis by turning the piles manually or mechanically. The ideal pile height is 4 to 8 ft tall, with a width of 14 to 16 ft. This size pile will produce enough heat and keep

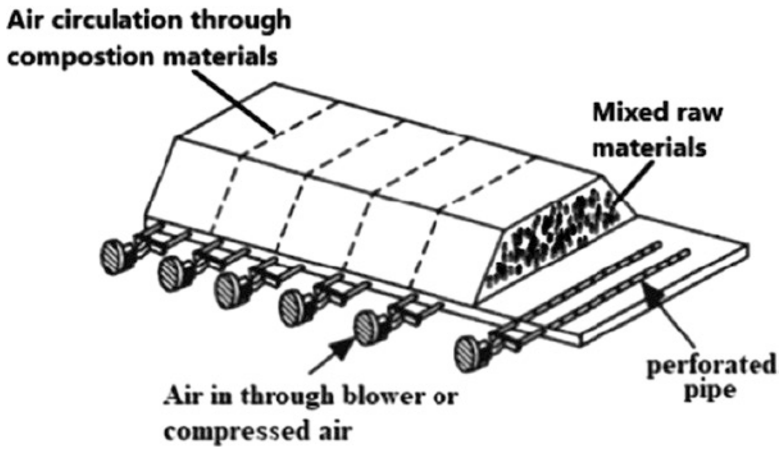


Fig. 1.34 Examples of an aerated static pile composting [67]

temperatures steady. It's small enough to allow oxygen to flow to the windrow. Windrows are often covered or placed under a shelter in a humid, arid environment to prevent water from evaporating. During rainy seasons, the pile's shapes can be changed such that water flows off the surface instead of being drained by the pile. This form can generate odours, which will need to be handled.

1.5.6.5 Aerated Static Pile Composting

This method of composting (Fig. 1.34) creates compost in a short time (between 1 and 6 months). It works well for larger volume generators of yard trimmings and compostable urban solid waste (e.g., food scraps, paper products), like local governments, landscapers, or farms, and is ideal for a relatively homogeneous mix of organic waste [67]. However, this approach does not work well for composting animal waste or grease from food processing industries; in this case, organic waste is mixed in a large pile. Layers of loosely stacked bulking agents (e.g., wood chips, shredded newspaper) are added to aerate the mound, allowing air to flow from the bottom to the top. The piles may also be placed over a network of pipes that supply or extract air from the pile. A timer or temperature sensors can be used to trigger air blowers. To avoid water from evaporating in a hot, arid environment, the pile may need to be covered or placed under a shelter. The pile will keep its warm temperature in the cold. Since passive airflow rather than active turning is used, aeration can be more difficult. It's also possible to bring the aerated static piles indoors with adequate ventilation. To buy, mount, and maintain equipment such as blowers, pipes, sensors, and fans, this method can necessitate a substantial financial investment as well as technical assistance.

1.5.6.6 In-Vessel Composting

This system can treat large quantities of waste with a smaller footprint as the windrow method, and it can handle almost any form of organic waste (e.g., meat, animal manure, biosolids, food scraps). Organic materials are fed into a drum, silo, concrete-lined trench, or other similar device using this process. This allows for precise monitoring of environmental factors, including temperature, humidity, and airflow. To ensure that the material is aerated, it is mechanically turned or blended. The size and capability of the vessel may differ. This process yields compost in a matter of weeks. Since the microbial activity must be balanced and the pile must cool, it will take a few more weeks or months until it is ready to use. This form produces no odour or leachate and can be used in extremely cold weather. However, this approach is costly, and proper operation can necessitate technical expertise.

1.5.7 Thermal Treatment Methods

Incineration is the heat treatment of solid wastes by controlled and total combustion. Solid waste incineration is a viable option in densely populated areas where landfills are unavailable. It results in energy recovery and hazardous waste degradation at high temperatures (between 980 °C and 2000 °C). The ability to reduce the original amount of combustible solid waste by 80–95% is one of the most appealing features of the incineration process. It also eliminates pathogenic bacteria. However, this process produced a high amount of air emissions which contains some invisible hazardous air pollutants that have a high potential health risk if not properly designed and operated. Hence, incinerators should be operated with care and in a proper way to minimize possible pollution.

An incineration is a form of producing steam via pyrolysis, gasification, and plasma and gasification. Several technologies have been established to make the processing of MSW with energy recovery cleaner and more cost-effective than ever before. Although older waste incineration plants generated a substantial amount of contaminants, recent regulatory changes and new technology have greatly reduced this issue. New and recent incinerators have been well built to minimize dioxin emissions from waste-to-energy plants. With the installation of sophisticated scrubbing and cleaning system, the waste-to-energy unit is also now ‘clean’ with less environmental impact

Incineration is costly, but it offers high energy returns while still being low on environmental impact and energy required to process MSW when properly built. It also necessitates a small footprint.

There are several types of incinerators, such as:

- Rotary kiln
- Fluidized bed
- Liquid injection

Table 1.14 Waste-to-energy facility in the US in 2018 [68]

Total capacity (by energy)					
Daily throughput		Gross electric capacity		Equivalent combined heat and power (CHP) capacity	
94,243 tons/day		2,534 MW		2,725 MW	
Number of facilities					
No. of operating facilities in the US		Ownership		Operation	
Operating facilities	75	Private	41	Private	65
States with waste to energy (WTE)	21	Public	34	Public	10
No. of facilities (by technology)			*No. of facilities (by offtake)*		
Mass burn	58		Electricity generation	58	
Refuse-derived fuel (RDF)	13		Steam export	3	
Modular	4		Combined heat and power (CHP)	14	

- Multiple hearth
- Catalytic combustion
- Waste-gas flare
- Direct flame

The first three types, namely, rotary kiln, fluidized bed, and liquid injection, are typically used in industry because of their large size use and their versatility. Furthermore, all three forms of incinerators can be run in pyrolysis or with very little oxygen.

Table 1.14 displays the number of waste-to-energy facilities in the United States' leading states in 2018. In Minnesota, there were eight waste-to-energy plants this year. The majority of facilities combust municipal solid waste without pre-processing using mass-burn technology [68].

Waste-to-energy plants in the United Kingdom are responsible for generating an estimated 7.77 terawatt-hours of electricity. Between 2015 and 2019, the estimated gross electricity generation of energy-from-waste (EfW) of waste-to-energy (WTE) plants increased by some 2.3 terawatt-hours (Fig. 1.35). There were 48 operational EfW power plants in the country as of 2019 [69]. A typical WTE plant is shown in Fig. 1.36.

1.5.8 Final Disposal by Landfilling

There are several disposal options for solid waste based on their composition and sources. These include the following:

- Direct burning of solid waste and dumping in the sea is not advisable.
- Dumping on land in landfills or dumpsites.

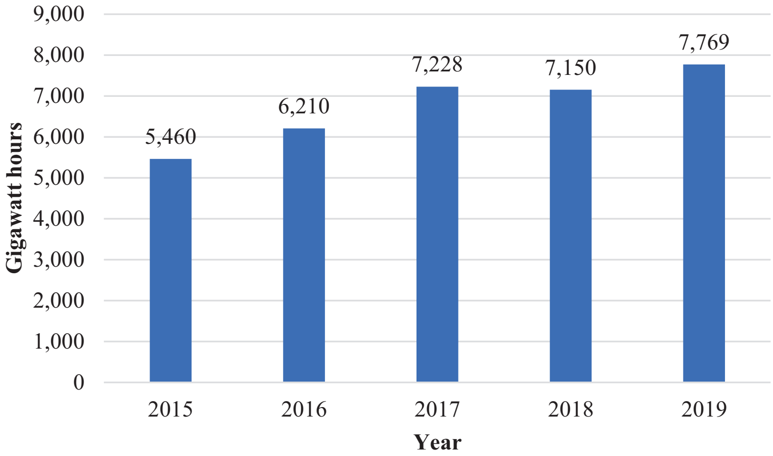


Fig. 1.35 Estimated gross electricity generation of energy-from-waste (EfW) incinerators in the United Kingdom (UK) from 2015 to 2019 (in gigawatt hours) [69]

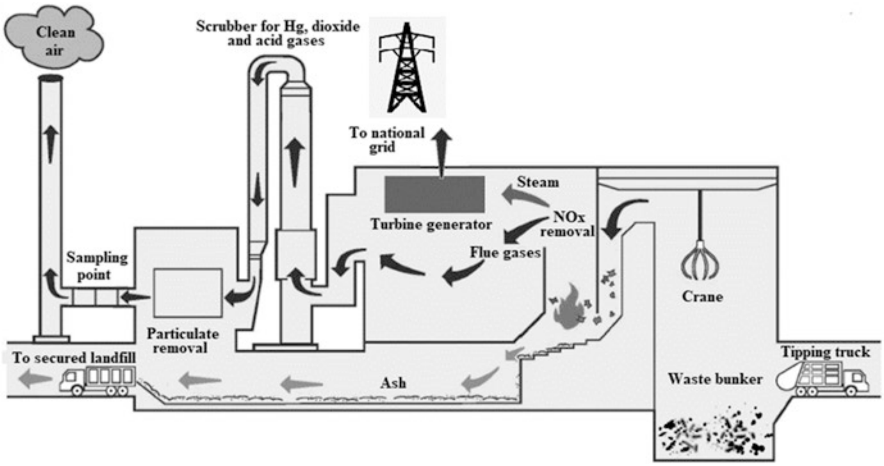


Fig. 1.36 A typical waste-to-energy incinerator

- Heat treatment – incineration, pyrolysis, gasification.
- Composting and reuse process in agricultural activities.
- Biological fermentation and digestion.

1.5.8.1 Introduction

Sanitary landfill is the most typical options for final waste disposal, especially in developing countries. It is the most basic, inexpensive, and cost-effective form of waste disposal. Many countries still consider landfills to be the oldest and most realistic method for disposing of solid waste. Many landfill sites are rapidly filling up due to the increase in waste volume produced daily, and many do not have a sufficient 3R facility. Due to land scarcity and increasing land prices, it is becoming more difficult to acquire new land for landfilling purposes, especially in urban areas.

Modern municipal waste disposal sites are well engineered with facilities to operate waste disposal. Nonetheless, this technique can be correlated to serious environmental problems if the disposal site is not adequately managed. The most popular form of land dumping is the mass dumping of waste into a designated area, normally a hole or a sidehill. Big machines compact the waste after it has been dumped. When the dumping cell is completed, a plastic sheet or soil is used to 'seal' it. A landfill allows solid waste to decompose before converting into a relatively inert and stable material. In fact, landfilling is an essential stage in waste management practices. However, the recycling process also generates non-recyclable products and residuals that require final disposal in a landfill. However, proper landfill design and monitoring after their closure are important issues for better and safe disposal and management of solid waste. This includes landfill gas control systems and leachate collection and treatment systems.

1.5.8.2 Landfills in the World

According to Worldatlas [70], nearly half of the world's population lacks access to basic waste collection and disposal facilities. More than 70% of MSW in the world is disposed of in landfills, with the majority of waste produced in low- and middle-income developing countries going to landfills. However, a substantial portion of the world's waste is still illegally disposed of on open dumpsites, which are particularly prevalent in low-income countries. These unregulated landfills are often located near cities. Pollution from open burning and pollution of groundwater are also common complaints from unregulated sites.

As of 2019, this figure gives a ranking of some of the world's largest dumpsites (Fig. 1.37). The Apex Regional Landfill in Las Vegas, Nevada, covered around 2200 acres of land this year. As the largest landfill in the United States, it is expected to last 250 years and contains close to 50 million tons of waste [70].

Figure 1.37 shows the world biggest landfill in 2019. The waste generation and number of a landfill in EU and other disposals/treatment method are given in Table 1.15 [71]. Table 1.16 presents the waste treatment methods used in ASEAN.

The majority of waste is actually discarded or disposed of in landfills around the world (Fig. 1.38) [70]. About 37% of waste is disposed of in a landfill, with 8% of that going to sanitary landfills equipped with gas collection systems. Around 31% of waste is discarded publicly, while 19% is recovered by recycling and composting,

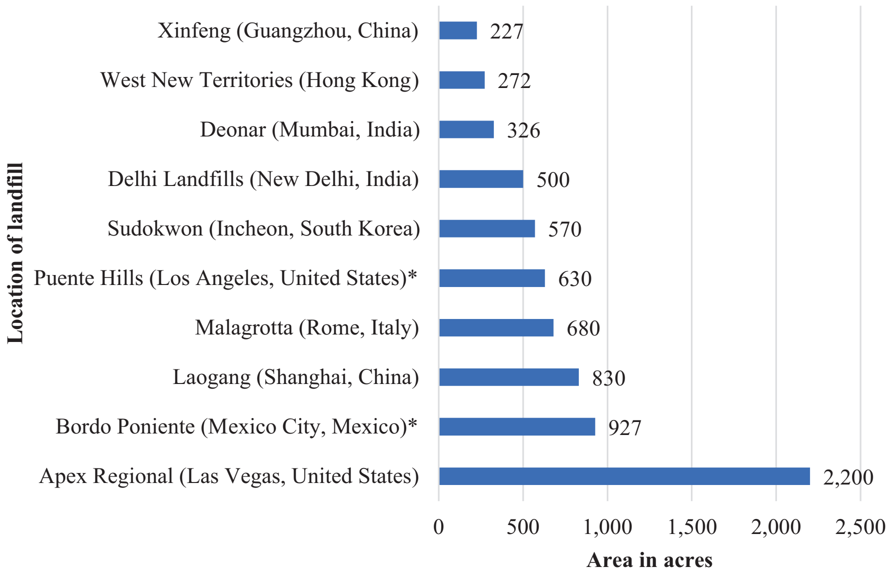


Fig. 1.37 Size of largest landfills globally as of 2019 [70]

and 11% is incinerated for final disposal. High- and upper-middle-income countries are almost entirely responsible for appropriate waste management or treatment, such as managed landfills or more stringently run facilities. Open dumping is widespread in low-income countries; 93% of waste is dumped in low-income countries, while only 2% is dumped in high-income countries. The Middle East and North Africa, Sub-Saharan Africa, and South Asia are the three regions that publicly spill more than half of their waste. The highest percentage of waste in landfills (54%) is found in upper-middle-income countries. In high-income nations, this figure drops to 39%, with 36% of waste diverted to recycling and composting and 22% to incineration. Incineration is mainly used in countries with high energy, high income, and limited property.

1.5.8.3 Categories of Landfill

Landfill sites can basically be divided into five categories, as being practised in Malaysia and in many countries. Its functional details are explained in Table 1.17. There are anaerobic landfills, anaerobic sanitary landfills, improved anaerobic landfills, semi-aerobic landfills, and aerobic landfills.

Table 1.15 Waste generation and treatment facilities (kg/capita) [71]

Country	Year	Source	Population (000s)	Waste Generated	Landfill	Incineration	Other recovery	Material recycling	Composting and digestion	Recycling rate
1. Germany	2015	OECD	81,202	628.6	59.3	196.7		300.7	114.6	66.10%
2. Wales	2016/17	Welsh Government	3100	512.8	48.7	125.8	0.3	327.2		63.80%
3. Singapore	2016	Singapore Government	5607	1394.6	543.1			850.5		61.00%
4. South Korea	2014	OECD	50,424	361.3	60.9	91.5		209.9	3.3	59.00%
5. Taiwan, ROC	2016	Taiwan EPA	23,492	317.6	3.9	127.4	2.6	159.7	24.5	58.00%
6. Netherlands	2016	Netherlands Government	16,981	560.6	12.5	209.7		171.5	145.7	56.60%
7. Austria	2015	OECD	8538	566.4	16.8	214.6		145.3	177	55.90%
8. Slovenia	2015	OECD	2067	448.1	101.7	76.5	14.3	208.1	34.3	53.90%
9. Belgium	2015	OECD	11,369	414.1	78.4	179.7		142.1	79.2	53.50%
10. Switzerland	2015	OECD	8129	741.8		350.6		236.7	154.5	52.70%
11. Italy	2016	Italy EPA (ISPRA)	60,656	496.2	122.5	96.7		153.4	107.4	52.60%
12. Luxembourg	2015	OECD	563	632.7	111.5	215.7		180.4	125.1	48.30%
13. Sweden	2015	OECD	9799	446.6	3.6	228.7		144.6	69.8	48.10%
14. Denmark	2015	OECD	5611	799.3	9.1	420.4		217.9	151.8	46.30%
15. Scotland	2015	SEPA	5400	457.2	213.1	41.9		202.1		44.20%
16. United Kingdom	2015	UK Government – DEFRA	64,532	489.2	115	153.5		133.3	79.4	43.50%
17. Norway	2015	OECD	4904	446	15.1	233.5	6.3	116.5	74.4	42.80%

(continued)

Table 1.15 (continued)

Country	Year	Source	Population (000s)	Waste Generated	Landfill	Incineration	Other recovery	Material recycling	Composting and digestion	Recycling rate
18. England	2016/17	UK Government – DEFRA	55,268	476.2	74.8	184	13.8	127.1	76.5	42.80%
19. Poland	2015	OECD	38,016	285.7	129.7	37.9		75.4	46	42.30%
20. Northern Ireland	2015/16	NI Government – DAERA	1900	510.1	205.4	90	1.4	122.3	91.1	41.80%
21. Australia	2015	OECD	23,941	557.2	260.6	64.9		231.7		41.60%
22. Finland	2015	OECD	5493	498.5	57.3	238.9		140.2	62.1	40.60%
23. France	2015	OECD	66,498	502.3	134.8	174.4		111.8	86.7	39.60%
24. Hong Kong, China	2014	Hong Kong Government	7240	776.2	492.7			283.6		36.50%
25. United States	2014	OECD	318,857	735.3	386.7	94.3		188.9	65.5	34.60%

Note: *OECD* Organisation for Economic Co-operation and Development, *EPA* Environmental Protection Agency, *ISPRA* Istituto Superiore per la Protezione e la Ricerca Ambientale (Italian National Institute for Environmental Protection and Research), *SEPA* Scottish Environment Protection Agency, *DEFRA* Department for Environment, Food and Rural Affairs, *DAERA* Department of Agriculture, Environment and Rural Affairs

Table 1.16 MSW management and disposal in ASEAN [9]

No	Country	Segregation at source (%)	Collection rate (urban) (%)	Recycling rate (%)	Management/treatment/disposal method				
					Composting	Incineration	Sanitary landfill	Open dumps	Open burning
1	Brunei Darussalam	<50	90	15			√	√	
2	Cambodia	<50	80	<50	√		√	√	√
3	Indonesia	<50	56–75	<50	√	√	√	√	√
4	Lao PDR	<50	40–70	<50					
5	Malaysia	<50	>70	50–60 (metal, paper, plastic)	√		√	√	√
				<50 (others)					
6	Myanmar	<50		70 (plastic, paper, metal)		√	√	√	
7	Philippines	50–70	40–90	20–23 (paper)	√		√	√	
				30–70 (Al)					
				20–58 (other metals)					
				23–42 (plastic)					
				28–60 (glass)					
8	Singapore	70	>90	50–60 (paper, horticulture)		√	√	√	
				>90 (Fe, CanD, used slag)					
				>80 (scrap tyre)					
				>80 (wood)					
				>50 (others)					
				60 (overall)					

(continued)

Table 1.16 (continued)

No	Country	Segregation at source (%)	Collection rate (urban) (%)	Recycling rate (%)	Management/treatment/disposal method				
					Composting	Incineration	Sanitary landfill	Open dumps	Open burning
9	Thailand	<50	>80	>90 (metal)	√	√	√	√	
				50–60 (paper, construction)					
				<50 (others)					
10	Vietnam	<50	80–82	>90 (metal)	√			√	
				>70 (plastic, e-waste)					
				50 (paper)					
				<50 (others)					

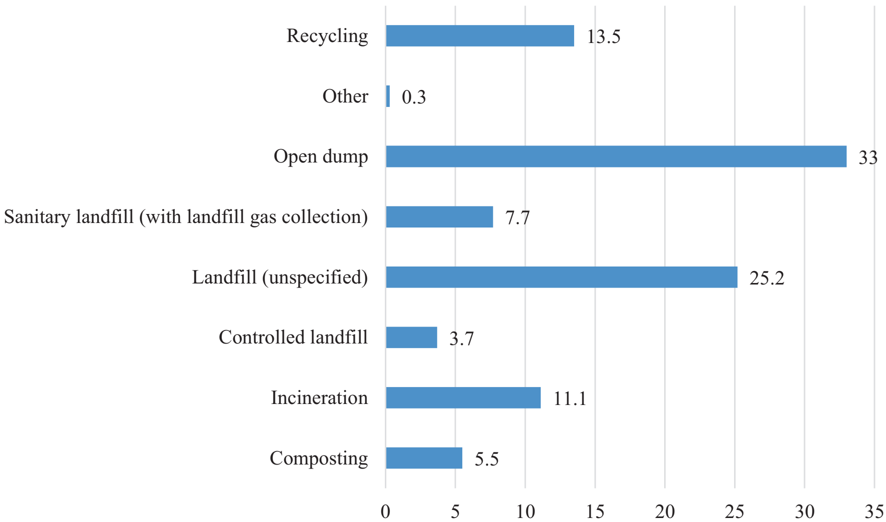


Fig. 1.38 Global treatment and disposal of waste (%) [8]

1.5.8.4 Landfill Leachate and Its Treatment

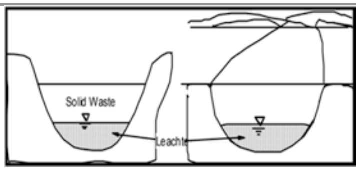
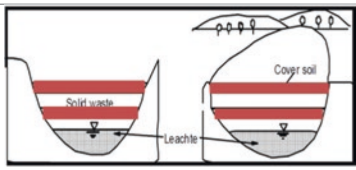
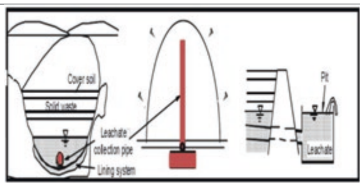
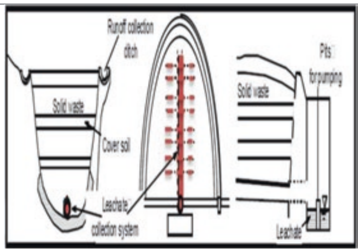
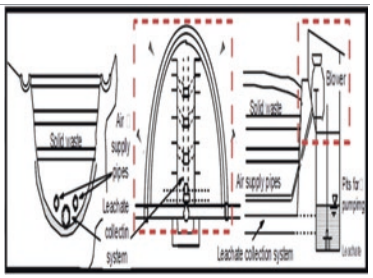
The accumulated municipal solid waste in landfill sites is exposed to several physicochemical processes, which result in the generation of highly polluted, dark-black liquid with a bad scent known as the leachate. Leachate is the fluid that disintegrates solid waste into leachate originates from the natural moisture and water in organic matter residue (product of the biologically decayed organic matter), as well as rainwater which percolates into the internal layers of the landfill and further enhances the solubility of suspended materials (Fig. 1.39).

The generation of leachate in landfill sites is also highly dependent on several main parameters such as the composition of MSW, site topography, area hydrogeological condition, age of solid waste, climate variations, humidity, and landfill site operation. Hence, it is important to protect the sustainability of the ecosystem by exploring appropriate environmentally friendly and effective treatment systems that could treat the leachate to such a degree that it is safe to be discharged into surface water resources (Fig. 1.40). A typical characteristic and classification of landfill leachate are shown in Table 1.18 [72–75].

The benefits and drawbacks of each physical and chemical treatment process are clearly displayed in Table 1.19.

Biological treatment is also only effective on young and intermediate leachates that have a high content of biodegradable organic matter ($BOD_5/COD > 0.5$). Physical–chemical approaches are more fitted to treat strong contaminant landfill leachate with a low biodegradability index of less than 0.1 and a high concentration of ammoniacal nitrogen. Both physical and chemical treatments were proved to be highly effective in treating old or stabilized leachate, which is hard to degrade [74].

Table 1.17 Types and characteristics of conventional landfills

Types	Characteristics	Illustrations
Anaerobic landfill	Solid waste is dumped into a dug area or a valley, and water is merged to allow for the anaerobic process to take place. This basic landfill has caused many serious environmental and human health problems by producing hazardous leachate	
Anaerobic sanitary landfill	This method layers solid waste with soil (sandwich form). Other characteristics are similar to those of anaerobic landfills	
Improved anaerobic landfill	Improvement was made to this design by adding a leachate collection system at the bottom of the pond. Other characteristics are similar to that of anaerobic landfills, except for the moisture content that is notably low	
Semi-aerobic landfill	In this model (Fukuoka method), O_2 is supplied spontaneously through the collection pipe to stabilize the solid waste. Therefore, the collection pipe is designed to be bigger than the previous model so that it can function to collect leachate and provide O_2. The aerobic process occurs here and increases the decomposition rate of solid waste	
Aerobic landfill	This method is designed to enhance the aerobic process of landfill systems since semi-aerobic landfills have performed well in terms of biodegradation and stabilization of landfills. Air and recirculation 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	

1.5.8.5 Design, Operation, and Challenges for Landfilling

Landfill siting: Site selection for landfill construction is one of the main challenges facing the local authority for managing the waste due to the difficulty in identifying a suitable location. One of the greatest challenges is the public concern who normally would object to sitting the landfill near their neighbourhood.

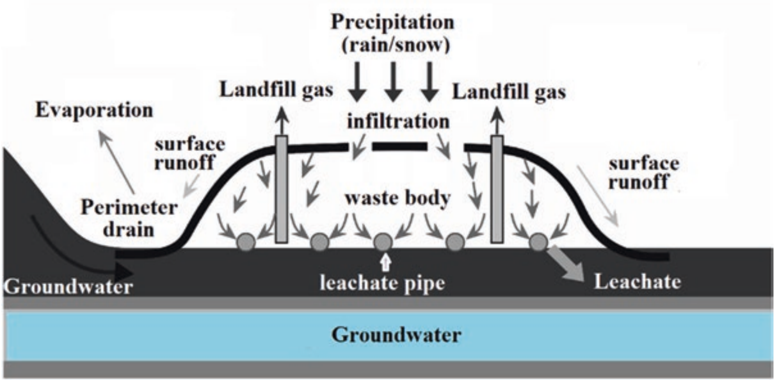


Fig. 1.39 Leachate formation in landfill

Landfill design: The landfill should be properly built to account for all various features, such as a suitable baselining system, leachate collection system, daily soil covering and final top liner, surface run-off collection and discharge system, gas emission system, and appropriate access facilities to the landfill, according to engineering principles and environmental codes of practice. The materials used in landfill construction and lining systems should have no negative impact on the environment, particularly groundwater. The landfill baseliner is made up of two upper and lower liners that compacted the soil. Furthermore, the primary aim of a baseliner is to reduce the risk of groundwater contamination due to leachate infiltration.

Gas emission: The natural decomposition of waste in the landfill involving microorganisms to break down the waste usually happens. The rate of degradation and decomposition of waste depends on the amount of water in and the temperature of the waste. During this process, the organic fraction of the wastes turns into CH_4 and CO_2. Moreover, some organics can be directly transformed into gas, such as cleaning materials waste. Typical constituents in the gas produced by municipal solid waste landfill are given in Table 1.20 [76].

Operation and maintenance for landfill: For the public's and environmental health's sake, the landfill should be constructed to meet safety requirements. The operation and maintenance should be managed well, including the following:

1. The waste in landfill should be identified by the operators to be non-hazardous, safe, and acceptable for disposal.
2. Daily covering the waste in the landfill.
3. Control the surface runoff to keep the waste decomposition in the landfill and not increase the leachate production.
4. The equipment used in landfill should be protective and should implement safety operation to the site workers and operators.

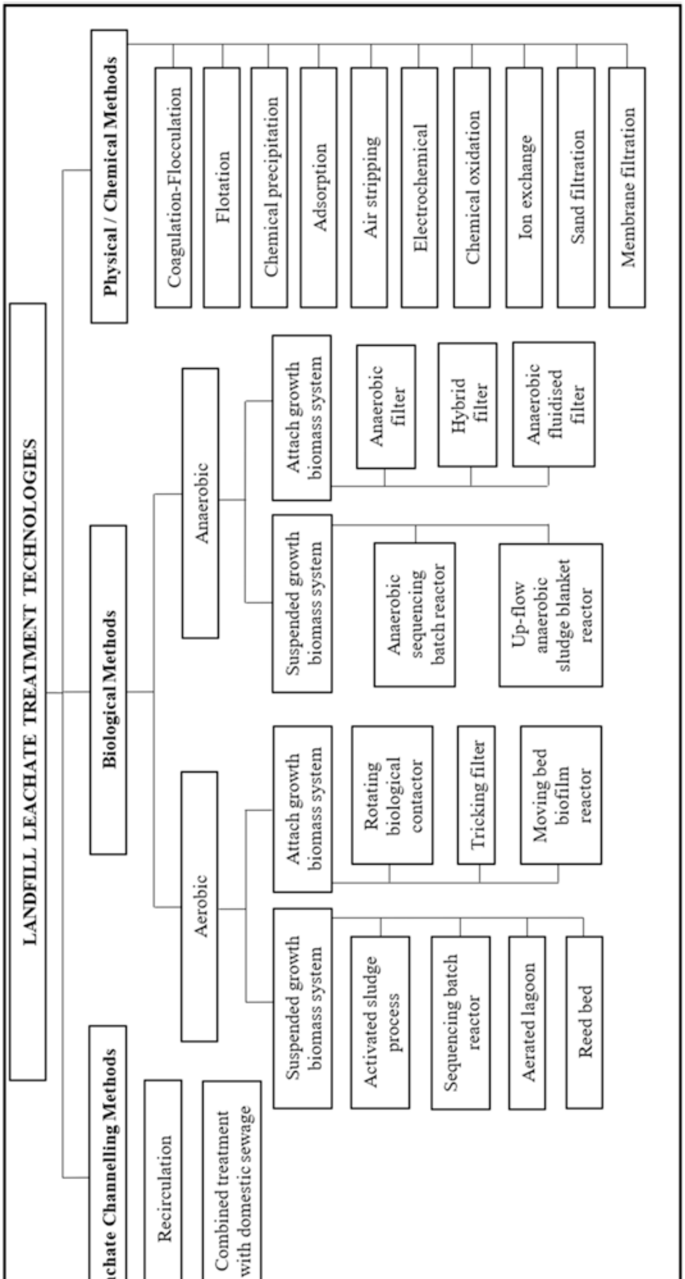


Fig. 1.40 Schematic diagram of landfill leachate treatment technologies

Table 1.18 Typical characteristics and classification of landfill leachate

No.	Parameter	Unit	Category of landfill leachate Young	Intermediate	Stabilized
1	Age	Year	<5	5–10	>10
2	pH	–	<6.5	6.5–7.5	>7.5
3	COD	mg/L	>10,000	5000–10,000	<5000
4	BOD_5/COD	–	>0.5	0.5–0.1	<0.1
5	Organic	–	80% (VFA)	5–30% (VFA + HFA)	HFA
6	NH_3-N	mg/L	<400	–	>400
7	Colour	PtCo	<1000	–	1500–7000
8	TOC/COD	–	<0.3	0.3–.05	>0.5
9	Conductivity	µs/cm	15,000–41,500	6000–14,000	–
10	Heavy metal	mg/L	Low	Low	Low
11	Biodegradability	–	Important	Medium	Low

Note: *VFA* volatile fatty acids, *HFA* humic and fulvic acids
Source: [72–75]

Table 1.19 Comparison of the physical and chemical methods in leachate treatment [71]

No.	Method	Leachate Y	M	O	Cost	Remark
1	Coagulant – flocculation	Poor	Fair	Fair	Low	High sludge production
2	Air stripping	Poor	Fair	Fair	High	Air pollution
3	Chemical precipitation	Poor	Fair	Poor	Low	Disposal of hazardous waste
4	Adsorption	Poor	Fair	Good	Low	Carbon fouling
5	Chemical oxidation	Poor	Fair	Fair	High	Toxic by-product
6	Electrochemical	Poor	Fair	Fair	High	High energy usage
7	Membrane filtration	Good	Good	Good	High	Membrane clogging
8	Ion exchange	Poor	Fair	Fair	High	High anion/cation
9	Flotation	Poor	Fair	Fair	High	High capital cost

Legend – *Y* young, *M* medium, *O* old

1.6 Integrated Solid Waste Management

Integrated solid waste management (ISWM) is a holistic procedure in managing solid waste that includes waste prevention, reduction, recycling, reuse, treatment, and disposal. How waste is handled from source to source is referred to as management (a cradle-to-grave approach). It also takes into account the waste management hierarchy, taking into account both direct and indirect impacts of waste transportation, processing, treatment, and disposal. From planning to design, commissioning, and service, solid waste management must be sustainable. ISWM may be implemented to create a long-term solid waste management system that is both environmentally and economically feasible also as socially acceptable.

For solid waste management, and ISWM solution is currently the most suitable scheme. ISWM promotes waste minimization by waste recovery, reuse, and

Table 1.20 Typical parameters found in landfill gas [76]

Component	Percentage (dry volume basis)
Methane	45–60
Carbon dioxide	40–60
Carbon monoxide	0–0.2
Nitrogen	2–5
Oxygen	0.1–1.0
Sulphides	0–1.0
Ammonia	0.1–1.0
Hydrogen	0–0.2
Trace constituents	0.01–0.6
Non-methane organic compounds	0.01–0.6

recycling through enhancing the quality of the total management system for all types of wastes, composting, incineration, and landfilling, in addition to waste treatment using conventional or advanced methods.

In waste management, a hierarchy (a structure in order of importance) may be used to prioritize actions for implementing initiatives in the community. Source reduction, recycling, waste transformation/processing, and landfilling are typically in the ISWM hierarchy. As shown in Fig. 1.14, a greater emphasis should be placed on source reduction and the least on final disposal. Prevention, minimization, reuse, recycle, energy recovery, and landfill disposal are the most widely sought solid waste management approaches.

Source reduction (reduce): At the top of the ISWM hierarchy, source reduction (reduce) entails lowering the volume and/or toxicity of wastes currently generated. Waste reduction can be accomplished by designing, processing, and packaging goods that have a low toxic content, a limited amount of material, or a longer useful life. Selective purchasing habits and the reuse of goods and resources can also help to reduce waste in the home, business, or industrial setting.

Reuse and recycling is the second-highest level in the hierarchy, and it entails (1) waste separation and collection; (2) preparation of waste materials for reuse, reprocessing, and remanufacture; and (3) reuse, reprocessing, and remanufacture of waste materials. Recycling is a vital part of reducing resource demand and the amount of waste that must be disposed of in landfills.

By putting in a Materials Recovery Plant, you will get a lot of recyclables back (MRF). This facility will sort all recyclable materials in a systematic manner, allowing them to be recycled and converted into new goods. This will also extend the landfill's useful life.

A proper waste segregation system is expected to enhance the overall recycling process and extend the landfill's life. At the same time, a 3Rs (recover, reuse, recycle) campaign should be prioritized. Residents should be reminded of the value of sorting their trash at a source. As soon as possible, a proper recycling programme must be devised. In the long run, education is extremely important. The 3Rs campaign is critical, and it is a difficult challenge that can only be accomplished through education. This could take a long time, but it should begin as soon as possible. Residents would be required to sort their trash at the point of collection. It is necessary to provide facilities. It will be important to assess performance and failure. It is hoped that by integrating these two methods (recycling at the point of usage by MRFs and recycling through education), the recycling rate will increase dramatically in the near future.

Waste processing/transformation: Waste transformation, the third rank in the ISWM hierarchy, entails the physical, chemical, or biological transformation of wastes. Physical, chemical, and biological transformations of MSW are usually used to (1) increase the performance of solid waste management operations and systems, (2) recover recycled and recyclable materials, and (3) recover conversion products (e.g., compost) as well as energy in the form of heat and combustible biogas. In most cases, waste transformation results in less landfill space being used. One well-known example is the reduction of waste volume by incinerator heat treatment.

Disposal by landfilling: In the end, something must be done with (1) the nonrecyclables and are of no further use; (2) the residuals after solid wastes have been separated at a materials recovery facility; and (3) the residuals after the waste-to-energy facility. Landfilling, which is ranked fourth in the ISWM hierarchy, includes the controlled disposal of wastes on or in the earth's mantle, and it is by far the most typical method of final disposal for waste residuals.

However, in order to implement a good integrated solid waste management system, various factors need to be investigated. This includes forecasting the waste amount and undertake various studies in terms of Environmental Impact Assessment (EIA), Socio-economic Impact Assessment (SoEIA), Sustainable Assessment (SA), Risk Assessment, and Life Cycle Assessment (LCA). On top of that, a Cost–Benefit Analysis and a feasibility study are also necessary.

1.7 Legislative Aspects of Solid Waste

Waste management laws regulate the transportation, handling, storage, and disposal of different forms of waste. Waste laws are usually enforced to discourage contamination by restricting or preventing the unregulated diffusion of waste materials into the atmosphere. They also contain legislation aimed at reducing waste generation and promoting waste recovery and recycling.

The method of classifying a substance as a 'waste' subject to regulation is known as waste identification. For example, in the United States and many other countries, non-hazardous municipal solid waste may be disposed of in landfills, whereas some metal scrap is considered hazardous and cannot be disposed of in landfills, but must instead be handled, stored, treated, and disposed of according to stricter regulations. The disposal options for a specific waste are governed by disposal requirements. Littering is the most popular and prevalent of these standards in many countries. Some waste should be handled in a certain way before being disposed of at a disposal site. The United States Environmental Protection Agency's Land Disposal Restrictions under the Resource Conservation and Recovery Act Subtitle C hazardous waste management programme, for example, prohibit hazardous waste from being disposed of on land (primarily in landfills) without prior approval.

Specific requirements for the construction and operation of a landfill may also be adopted, particularly with regards to the need to adhere to location restrictions in order to avoid surface and ground water contamination. It also manages operation policies to eliminate dust and other annoyances (leachate and gases), as well as environmental control programmes that ensure compliance.

There is also international law, which includes agreements on international hazardous waste transportation and disposal. European Agreement Concerning the International Carriage of Dangerous Goods by Inland Waterways (AND), Geneva, 2000; Convention to Ban the Importation of Hazardous and Radioactive Wastes into Forum Island Countries and to Control the Transboundary Transport and Management of Hazardous and Radioactive Wastes, Geneva, 2000; Convention to Ban the Importation of Hazardous and Radioactive Wastes into Forum

The Resource Conservation and Recovery Act (RCRA), which was passed in 1976, is the primary federal legislation regulating the management of solid waste and hazardous waste in the United States. The federal Superfund program in the United States was gazetted by the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), which is managed by the United States Environmental Protection Agency (USEPA). The program's aim is to inspect and clean up hazardous substance–contaminated areas. The United States Environmental Protection Agency (USEPA), which regulates the hazardous waste generation and disposal; the United States Department of Transportation (DOT), which regulates hazardous waste transportation; and the Nuclear Regulatory Commission (NRC), which regulates nuclear waste, are among the regulatory bodies in the United States [78–81].

Waste legislation in the United Kingdom is primarily derived from EU governance and transposed into UK law through Statutory Instruments. In response to the rising waste amount disposed of in landfills, the government levied a Landfill Tax on some forms of waste deposited in landfills starting in October 1996. Landfill operators who were authorized under the Environmental Protection Act (EPA) or the Pollution Control & Local Government Order 1978, for example, had until 31 August 1996 to register their tax liability. The tax is seen as a critical means for the UK to attain its objectives for landfilling biodegradable waste specified in the Landfill Directive. Other advanced waste management systems with higher tipping charges are more financially attractive by raising the cost of landfill. The Landfill Directive, also known as Council Directive 1999/31/EC of 26 April 1999, is a European Union directive that governs landfill waste management in the EU. By 16 July 2001, all of its member states had adopted it. The Directive's ultimate goal is to 'prevent or mitigate as much as possible negative environmental impacts from waste landfilling, as well as any resulting danger to human health'. This legislation has far-reaching consequences for waste management and disposal. Following that, in 2000 and 2002, waste targets for England and Wales were adopted, focusing on recycling, composting, and energy from waste (EFW) technologies for MSW recovery [11].

The new European waste strategy is based on the Landfill Directive [31], the Waste Incineration Directive, and the Packaging and Waste Packaging Directive [31, 77]. The obligatory targets set out in the EU Landfill Directive, which was adopted on 26 April 999, and entered into effect on 16 July 1999, would require the UK and other EU countries to lessen the biodegradable portion of municipal waste disposed of to landfill to 75% of the amount in 1995 by 2010. Similarly, by 2013, this will have to be reduced to 50%, and by 2020, it will have to be reduced to 35%. In 2002, the Welsh Assembly Government released the 'Wise About Waste' National Waste Strategy for Wales, which aims to ensure compliance with European waste management directives. According to the goals, a minimum of 15% of MSW must be recycled or composted by 2003/2004, with a 5% minimum goal for each group. By 2006/2007, the target has risen to 25%, with a minimum of 10% for each group. By 2009/2010, the overall goal is set at 40%, with a minimum goal of 15% for each group [77].

The majority of ASEAN countries have already enacted environmental legislation as well as other green growth, sustainable development, climate change policies, regulatory frameworks, and strategies. Waste management legislation exists in Indonesia, Malaysia, the Philippines, and Thailand. The Ministry of the Environment is largely responsible for waste management policy. Other related ministries are also in charge of particular waste sources (for instance, the Ministry of Health for Hospital Waste, Ministry of Local Government for Domestic Waste). Municipalities and state or local governments are directly responsible for waste management systems at the local level.

The Local Government Act of 1976, the Environmental Quality Act of 1974, the Town and Country Planning Act of 1976, and the Streets, Drainage and Construction Act of 1976 are the four subsidiary laws that regulate solid waste management in Malaysia. Local governments are currently the most influential institution active in solid waste management. As a result, the Technical Section of the Local Government Department in Malaysia's Ministry of Housing and Local Government proposed a National Solid Waste Management Action Plan, also known as the Action Plan for a Beautiful and Clean Malaysia, in 1988. (ABC). The Solid Waste and Public Cleansing Management Act 672, 2008, and the Solid Waste and Public Cleansing Management Corporation Act 673, 2008, were both published in the *Gazette* this year.

1.8 Concluding Remarks

This chapter has endeavoured to provide an overall image of the nature of the solid waste crisis, both qualitatively and quantitatively, as well as the issues surrounding its management. The rapid growth of waste volumes and a diverse waste composition of new and emerging waste sources are among the various environmental challenges in waste management. In both developed and developing countries, proper solid waste management is essential for maintaining human health and the environment. Full compliance with waste management hierarchy systems is needed for integrated municipal solid waste management. Minimizing and reducing waste is a critical component of effective urban solid waste management. Recycling and reuse of waste were considered an important option for improving the economy and reducing the quantity of final waste disposal. Despite the numerous disposal options, landfilling is commonly regarded as a viable choice for the disposal of urban solid waste around the world. Many local governments are facing a major challenge: Growing waste collection volumes and the need to meet more rigorous regulatory requirements in disposal operations necessitate increased capital and operating revenue reserves.

In the overall management system, both short- and long-term options are important. Many countries face major challenges in terms of infrastructure, technology, funding, governance, and stakeholder involvement. These difficulties, on the other hand, could become opportunities if we change our perspective of waste as a resource. Although improving waste recycling rates and waste to energy (WTE) technologies and methods, front-end solutions, such as frameworks for waste reduction/prevention through sustainable consumption and resource management, must also be considered. For a successful recovery system, all countries should encourage segregation at the source. Certain incentives, such as a recycle for life card that rewards people who send recyclables to recycling centres with money, maybe devised to encourage people to recycle. A model that works A proper value chain in the entire solid waste management system (including waste generation, segregation, collection, transfer, treatment, and disposal, as well as resource recovery via the 3Rs) should be designed so that waste can be converted into income and the new digital economy cycle can be accelerated. Furthermore, every country should look into producing co-benefits from the waste sector, such as reduced greenhouse gas (GHG) emissions, which facilitates the achievement of sustainable development goals (SDGs), and so on. Greater coordination between public and private organizations in waste value chains would help pool resources and gather shared responsibilities for waste management, particularly in terms of selecting and implementing environmentally sound technologies (ESTs) that are suitable for the local waste characteristics [78–81].

Furthermore, the design and implementation of the right mix of legislative, economic, and social instruments, as well as incentives for strong enforcement monitoring by all relevant stakeholders, are critical. Improving operational performance and encouraging interdepartmental/agency collaboration is also critical. Alternative and creative financing methods, such as public–private partnerships (PPPs), public funding initiatives (PFIs), and the implementation of the polluter pays concept, will bolster existing revenue streams. Companies that are doing 'healthy' in terms of waste recycling should be given tax breaks.

Glossary

US Environmental Protection Agency (USEPA) is the United States federal government agency whose mission is to protect human and environmental health.

Environmental Impact Assessment (EIA) is the process of examining the anticipated environmental effects of a proposed project from consideration of environmental aspects at the design stage

American Society of Mechanical Engineers (ASME) is an American professional association that promotes the art, science, and practise of multidisciplinary engineering and allied sciences around the world.

Cost–benefit analysis (CBA) is a systematic process that businesses use to analyse which decisions to make.

Life Cycle Assessment (LCA) is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service.

Material Flow Analysis (MFA) is an analytical method to quantify flows and stocks of materials in a system.

Socio-economic Assessment (SoEA) is the analysis of social, cultural, economic, and political conditions of individuals, groups, communities and organizations.

Risk Assessment (RA) is the process of identifying and analysing potential events that may negatively impact individuals or the environment and making judgements on the tolerability of the risk on the basis of a risk analysis.

Strategic Environmental Assessment (SEA) is a systematic decision support process aiming to ensure that environmental and possibly other sustainability aspects are considered effectively in policy, plan, and programme making.

Resource Conservation And Recovery Act (RCRA) is the principal federal law in the United States governing the disposal of solid waste and hazardous waste, which was enacted in 1976.

United Nations Environment Programme (UNEP) is the leading environmental authority in the United Nations system.

Volatile fatty acids (VFA) are short-chain fatty acids composed mainly of C2–C6 carboxylic acids produced in the anaerobic digestion process, which does not need sterilization, additional hydrolysis enzymes, or high-cost pre-treatment step.

Air Pollution Control Residues (APCr) is typically a mixture of ash, carbon, and lime.

Brominated flame retardants (BFR) are mixtures of man-made chemicals that are added to a wide variety of products, including for industrial use, to make them less flammable.

Chlorofluorocarbons (CFC) are fully or partly halogenated paraffin hydrocarbons that contain only carbon (C), hydrogen (H), chlorine (Cl), and fluorine (F), produced as a volatile derivative of methane, ethane, and propane.

Hydrochlorofluorocarbons (HCFC) are compounds containing carbon, hydrogen, chlorine, and fluorine.

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