CHAPTER 5

Influential Aspects in Waste Management Practices

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INTRODUCTION

Between 1880 and 2017, global surface temperatures have increased by 1°C. Similarly, the concentration of carbon dioxide has witnessed a surge to greater than 400 ppm, the highest level in the past 650,000 years. This increase in temperature will elevate sea levels, which will ultimately affect the livelihood of millions of people across the world. The average global sea levels are rising by 3.2 mm/a [1]. Most climate change models predict that limiting global warming to less than 1°C may not be possible by the end of this century. Global warming is caused by activities such as industrialization, use of fossil fuels, which release greenhouse gases (GHGs) and contribute to global warming [2].

Human-led industrialization has caused a surge in the economy that has radically transformed our consumption patterns. This changing pattern has left a human trail across the globe in the form of waste. Today, the global solid waste generation has reached about 2 billion tonnes/a [3]. A strong correlation between economic growth and waste generated can be observed, highlighting the changes in consumption patterns. However, only a few countries in the world manage their waste disposal and recovery efficiently.

Several components within the wastes generated are valuable resources that are typically unused and dumped, polluting our environment, rivers, and oceans. For example, plastic bags are produced from fossil sources that leave a significant trail in the oceans affecting the flora and fauna of the aquatic environment. If plastic bags are recycled efficiently, the need for fossil sources may decrease, reducing our emissions and strengthening our fight against climate change [4]. On the other hand, waste generation is inevitable. Thus a fine balance between waste production and treatment/recovery is necessary.

There are several aspects in providing effective waste management practices. These include the use of the appropriate technology, which is economical, backed by the government in the form of policy and has gained support from the public. These interventions affect waste management practices across the globe. However, the complexity in this practice is the interactional effects of these factors that can adversely affect waste management [5].

This chapter attempts to address the influential aspects of an effective waste management practice, including an overview of global waste facts, technologies available, technical issues in waste management, and economic, sociocultural, and political factors. Finally, a case study that compares the waste management practices in different countries is presented. This chapter highlights issues to be considered that go beyond the conventional and technical side of waste management practices.

GLOBAL WASTE—FACTS AND FIGURES

Global solid waste generation is on the rise, with more than 2 billion tonnes/a of waste produced. This increase in waste generation is influenced by several factors including expanding economies, new products, change in mind-set among the public, consumerism, increases in income, increase in population, etc. [6]. A global heat map of per capita solid waste generation per day is highlighted in Fig. 5.1 [3,7]. It is evident that the developed countries exceed the developing countries in terms of waste generation. This is primarily due to the socioeconomic status and the capacity of purchasing

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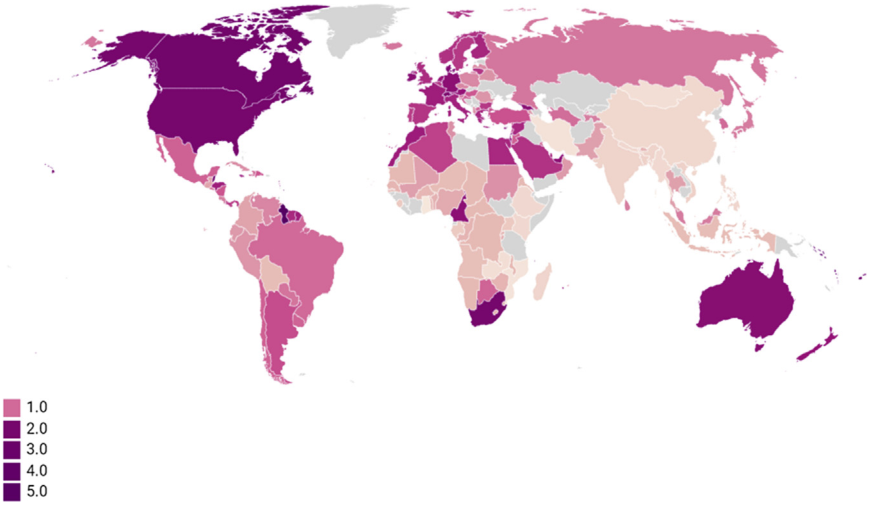

FIG. 5.1 Global heat map of per capita solid waste generation per day (kg/capita/d).

power among the people in these countries. The developed countries, including the United States, Canada, the European Union, and Australia, produce significantly more waste than the third-world countries [6].

In the past, products have been developed with the intention for use, but not designed to include for disposal/treatment, i.e., the end of a product's life cycle. This design approach has caused difficulties environmentally in terms of global warming and climate change. It is necessary to change this consumption pattern to reflect sustainability into the consumption cycle and for the product waste to become a part of it. Certain countries have established a polluter pays principle and also indicated the producer responsibility to reflect this change in a product cycle [8]. However, these laws are enacted mainly in developed countries. There are several factors that affect global solid waste generation and its treatment patterns. This includes access to affordable technology, economic conditions, sociocultural influences, and political directives. There is a strong correlation between the gross domestic product and the waste generated in countries. This is an almost linear correlation (Fig. 5.2). As the economy of many countries continues to expand, this correlation poses a serious threat how the wastes generated will be treated and processed.

As products are produced, and utilized, at a faster rate, it is necessary to develop suitable technologies for waste treatment. With more products being produced, fewer resources will be available in the future to sustain these requirements. It is becoming extremely important that the technologies developed for waste management should consider sustainable resource recovery mechanisms.

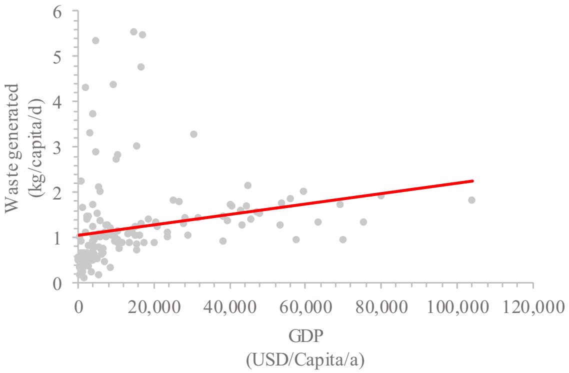

FIG. 5.2 Correlation between gross domestic product (GDP) in USD versus waste generated (kg/capita/d).

WASTE MANAGEMENT TECHNOLOGIES

There are a variety of waste treatment technologies; the long-established technology is simply landfilling. Other available technologies include composting and recycling. These technologies have been widely employed to treat various types of wastes. Alternatively, advanced waste treatment technologies have attracted increasing attention and have been explored for the purpose of waste-to-energy conversion. These advanced technologies include biological (e.g., anaerobic digestion and fermentation) and thermal/thermochemical technologies (e.g., incineration, pyrolysis, and gasification), which are outlined in Table 5.1 in terms of the conversion process, conditions, main products, and by-products. These technologies are not necessarily more complex than the established technologies, but

TABLE 5.1
Advanced Waste Treatment Technologies.

Conversion Process	Conditions	Main Products	By-Products
Anaerobic digestion	35–55°C, anaerobic environment, pH 6.5–7.5	Biogas (around 60% CH_4 and 40% CO_2)	Digestate (used as fertilizer/for soil amendment)
Hydrogen fermentation	35–55°C, anaerobic environment, pH 5.5–6.5	Biohydrogen (around 60% H_2 and 40% CO_2)	Volatile fatty acids (used for downstream chemicals)
Ethanol fermentation	30–35°C, anaerobic environment, pH 4.5–6.0	Ethanol and CO_2	Remaining feedstock (used as animal feed)
Incineration	800–1000°C, air, oxygen	Heat, electricity	Ash
Gasification	800–900°C; air, oxygen, or steam; 1–30 bar	Syngas (CO, CH_4, N_2, H_2, CO_2)	Ash
Pyrolysis	400–1200°C, the absence of oxygen	Syngas, bio-oil	Biochar (used for soil amendment, activated carbon)

they exhibit many advantages with respect to the reduction of volume and destruction of toxic organic compounds, and energy recovery. However, the economics need to be carefully evaluated when using the advanced waste treatment technologies. This section will discuss the advantages and the major challenges associated with these advanced waste treatment technologies.

Anaerobic Digestion

Anaerobic digestion is a series of biological processes in which diverse microorganisms break down biodegradable materials in the absence of oxygen. Wet organic wastes such as food wastes, animal slurries, and agricultural wastes are preferable feedstocks for anaerobic digestion. One of the end products is biogas (mainly containing 60% methane and 40% carbon dioxide), which is combusted to generate electricity and heat, or can be upgraded into renewable natural gas and transportation fuels. The other product is nutrient-enriched digestate, which can be used as soil conditioners or fertilizers. Anaerobic digestion has many environmental benefits including the production of a renewable energy platform, the possibility of nutrient recycling, and the reduction of waste volumes [9]. As a result, anaerobic digestion has, in the recent years, received increasing attention in a number of countries. For example, the total number of biogas plants in Europe was 14,572 as of 2013 and Germany has the most developed biogas industry, with around 9000 plants in operation [10]. In Asian countries, the biogas industry is booming; for example, the biogas production in 2015 in China reached 19 billion m^3, with an average annual growth rate of 6.3% since 2010.

When considering the application of anaerobic digestion systems, the feedstock is a key factor affecting the performance of digestion. Wet organic wastes such as food waste and animal slurries typically contain abundant biodegradable components that can be used for biogas production. However, the individual feedstock may have a suboptimal carbon-to-nitrogen (C/N) ratio, which can lead to an unstable digestion process. Carbohydrates are more favorable substrates than proteins. The excess protein content in feedstocks can lead to a low C/N ratio (typically below 10); this would be a critical issue for long-term monodigestion. It is known that anaerobic degradation of protein compounds produces ammonia. High ammonia concentration in the digester can inhibit methanogens, causing volatile fatty acid accumulation and digestion failure. To address this issue, codigestion of carbohydrate-rich and protein-rich feedstock has been carried out to achieve a balanced C/N ratio, thus increasing the activity of microorganisms in digestion associated with an increased biogas yield. Research has shown that codigestion of municipal waste and food waste can help improve biogas production by up to 40%–50% compared with monodigestion of food waste alone [11]. It has been demonstrated that biogas yield from the mixture of wastewater sludge and food waste increased linearly with an increased fraction of food waste, and addition of 35% of food waste in the mixture exhibited not only a higher methane yield but also an accelerated methane production [12].

Another issue that may affect the application of anaerobic digestion is the relatively long digestion time (typically 20−40 days) due to the long duration of the microbial reactions. The major biological processes involved in anaerobic digestion include four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Fig. 5.3), and each step requires certain types of microorganisms. Most researchers have reported that the rate-limiting step for complex organic substrates is the hydrolysis step, which is ascribed to the formation of toxic by-products or non-desirable volatile fatty acids formed during the hydrolysis step. While methanogenesis is the rate-limiting step for easily biodegradable substrates, due to the relatively low growth rate of methanogens. To accelerate the hydrolysis and enhance subsequent methane productivity, a variety of pretreatment options, such as mechanical, thermal, chemical, or biological processes, or a combination of these, have been developed at laboratory or pilot scale with various levels of success [13−15]. However, a systematic assessment of different pretreatment options is quite necessary for deciding which one would be the most suitable from an industrial point of view.

Fermentation

Fermentation technologies can be employed to produce either biohydrogen or bioethanol from wet organic wastes, such as food waste, agricultural waste, sewage sludge, using different microorganisms. Before fermentation, some wastes require saccharification or hydrolysis for converting carbohydrates (such as cellulose and starch) into sugars.

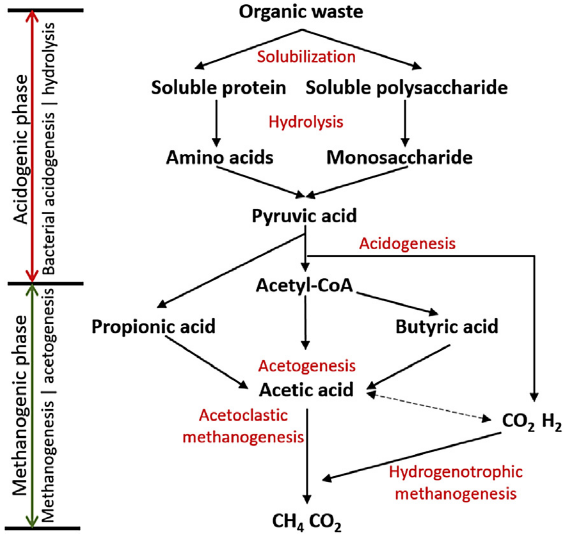

FIG. 5.3 Metabolic pathway for methane production via anaerobic digestion.

Biohydrogen is usually produced through dark hydrogen fermentation, during which hydrogen-producing bacteria, such as *Clostridium* and *Enterobacter*, can convert fermentable sugars to hydrogen and volatile fatty acids. Hydrogen is a potentially versatile energy carrier that could alter the use of liquid fossil fuels because hydrogen has a high energy density per unit mass of 122 kJ/g, which is 2.8-fold higher than that of hydrocarbon fuels [16]. In addition, the combustion of hydrogen produces only water as a by-product, contributing to a favorable outcome for the reduction in GHG emissions. Biohydrogen production through dark hydrogen fermentation is still in its infancy and most studies are based on pilot scales. The critical challenges of hydrogen fermentation lie in the low hydrogen conversion efficiency and unstable hydrogen production, partly because of the formation of various by-products. The theoretic yield of hydrogen through dark fermentation is 4 mol/mol of glucose ($C_6H_{12}O_6 + 2H_2O = 2CH_3COOH + 2CO_2 + 4H_2$) [17]. However, the reported data are typically below 2.5 mol/mol glucose in the state-of-the-art literature [17−19]. For example, the hydrogen yields of wild *Enterobacter aerogenes* (a typical species of hydrogen-producing bacteria) are reported as approximately 1.0−1.8 mol/mol of glucose [20]. The low yields are due to the fact that the bacterial strain is sensitive to and inhibited by operational parameters such as particular pH ranges, accumulated hydrogen, and volatile fatty acids.

With regard to bioethanol production, this fermentation process mainly converts sugars to bioethanol. As compared with biohydrogen production, bioethanol production is a more mature technology. The basic steps for large-scale production of bioethanol are fermentation of sugars, distillation, dehydration, and denaturation (optional). For bioethanol production from the cellulosic materials of wastes, effective pretreatment and enzymatic hydrolysis are required to produce a high concentration of glucose. Fermentation can then convert glucose to ethanol by microbes, such as *Saccharomyces cerevisiae*, *Escherichia coli*, *Zymomonas mobilis*, *Pachysolen tannophilus*, and *Candida shehatae*. Ethanol is broadly used as a liquid biofuel for transportation and has a great potential as a substitute of gasoline in the transport fuel market. But the cost of bioethanol production is higher than that of fossil fuels. To address this issue, progressive research is needed to reduce the cost of enzymes and to select robust microorganisms with high tolerance to inhibitory compounds [11].

Incineration

Incineration is a relatively mature waste treatment technology that involves the combustion and conversion of wastes into heat, flue gas, and ash [21]. It is the thermal degradation and decomposition of wastes in the presence of oxygen at temperatures of 800—1000°C. The heat from the combustion process can be used to operate steam turbines for energy production, or for heat exchangers in industry. The ash is mostly formed by the inorganic composition of the wastes and may be carried by the flue gas in the form of solid particulates. The flue gases must be cleaned to remove the gaseous and particulate pollutants before they are dispersed into the atmosphere. Incinerators are capable of reducing the volume of original solid wastes by up to 80—85%, and thus they significantly reduce the necessary volume for disposal [11]. In addition, incineration has particular benefits for the treatment of certain waste types such as clinical wastes and certain hazardous wastes where pathogens and toxins can be completely destroyed by high temperatures [22].

The major issue with incinerators is the potential pollution associated with incineration of waste. Emissions include the following elements and compounds: sulfur, chlorine, fluorine, N_2, CO, CO_2, NO_x, SO, polychlorinated dibenzodioxine, furan, methane, ammonia, hydrochloric acid, and hydrogen fluoride [23]. Extensive efforts have been made to control the pollutant emissions, such as by modifying the fuel composition, the moisture content of the fuel, the particle size of the fuel, and the incinerator configuration. For example, an electrostatic precipitator was used to remove dioxin in an incinerator, resulting in removal efficiencies greater than 90% for all congeners and homologs of dioxins [24].

Gasification

As another thermal approach for waste treatment, gasification is similar in principle to incineration. The energy produced from incineration is high-temperature heat, whereas combustible gas is often the main energy product from gasification. Gasification converts wastes into a combustible gas mixture by partially oxidizing wastes at high temperatures, typically in the range of 800—900°C. The low-calorific-value gas produced can be burned directly or used as a fuel for gas engines and gas turbines. The product gas (a mixture of CO, H_2, CO_2, and H_2O) can be used as a feedstock in the production of chemicals (such as methanol). The gasification of solid waste includes a sequence of successive endothermic and exothermic steps, with respect to the reactants and products (Fig. 5.4).

Gasification of municipal solid waste (MSW) and biomass as an energy recovery method has been widely studied all over the world. Several types of research on biomass gasification technologies have been conducted in the European Union and the United States and most of them are in the laboratory or demonstration phase [25]. Gasification has several advantages over the traditional incineration technology, primarily in terms of

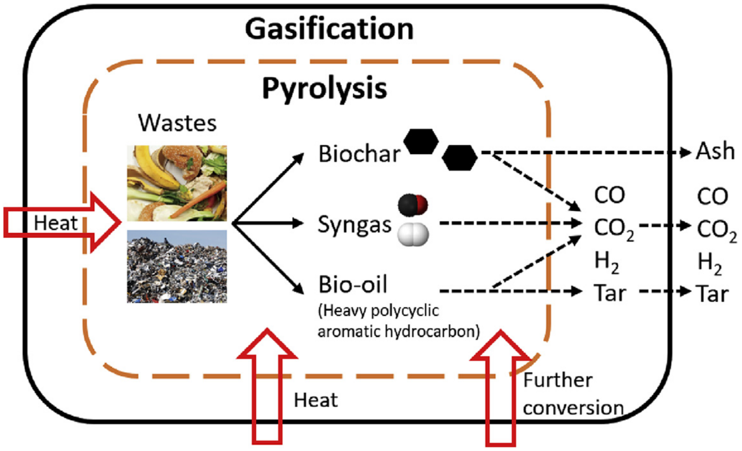

FIG. 5.4 Schematic of pyrolysis and gasification for waste treatment. (Adapted and modified from [25].)

more acceptable cost and the flexibility of coupling the operating conditions (such as temperature and equivalence ratio) and the reactor configurations (such as fixed bed, fluidized bed, entrained bed, vertical shaft, moving grate furnace, rotary kiln) to obtain syngas, which is suitable for use in different applications [11]. However, the variable characteristics of various wastes tend to make gasification much more challenging; the variation of feedstock properties has a major impact on the design, performance, maintenance, and cost of gasification, and ultimately on its feasibility [26]. Even if a number of significant applications do exist, the extreme challenges of waste gasification prevent it from consideration as an established commercial option: operating experience is limited and data on actual performance, reliability, and costs are incomplete as well, thus making comparisons with conventional technologies very difficult.

Pyrolysis

Pyrolysis is a technology that breaks down organic materials in the absence of oxygen to produce liquid (bio-oil), gaseous (syngas), and solid (biochar) products, as illustrated in Fig. 5.4. Syngas comprises mainly of CO and H_2 (together 85%) with a small proportion of CO_2 and CH_4. The bio-oil produced through pyrolysis typically has a heating value of around 17 MJ/kg. The pyrolysis process can occur in the temperature range of 400−1200°C. Although the product yield depends on various operating parameters, generally low temperature and high residence time favor biochar production [27]. Pyrolysis has been investigated as an attractive alternative to incineration for waste disposal. The pyrolysis process conditions can be optimized to produce a solid char, gas, or liquid/oil product, indicating that a pyrolysis reactor can act as an effective waste-to-energy converter. When compared with the conventional incineration plant that runs in the capacity of kilotonnes (kt) per day, the scale of the pyrolysis plant is more flexible and the output of pyrolysis can be integrated with other downstream technologies for product upgrading. The existing pyrolysis technologies seldom run alone with gas, bio-oil, and biochar output as end products, most of them are combined with gasification, combustion, and smelting. The combination with gasification produces fuel gas of moderate calorific value, and this will be a competitive choice in the future. However, at the same pyrolysis-based technologies are expensive and may not be affordable compared to commercial waste treatment methods.

FACTORS AFFECTING WASTE MANAGEMENT

There are several factors that affect sustainable waste management practices. The problems are typically different depending on the country and thus it is a multidimensional localized problem that cannot be solved by a single solution. A combination of different aspects needs to be assessed to reach sustainable solutions. There are four distinct aspects of interest in waste management: technology, economics, sociocultural aspects, and politics.

Technology

The developed world has access to high-end technologies because of the increased efforts in innovation, research, and development. However, one technology that works in a particular country may not be as effective in another because of the local conditions and requirements. For example, Japan has limited land availability that drives incineration as the preferred waste treatment technology over other forms of treatment methods [3]. Waste management technologies should be developed to reflect the 5R principles (reduce, reuse, recycle, recover, and refuse) [28]. Yet the bottom-up approach has been practiced more than the top-down approach (Fig. 5.5). Many countries landfill/dump waste, and some developed countries use energy recovery and recycling. For a sustainable future, more emphasis needs to be placed on the reduce and reuse concepts.

Conventional waste management technologies have less scope in the market in terms of recycled materials. Most present-day technologies can sort similar materials but not a composite such as food packaging [29]. Other technologic aspects such as waste collection systems need to be simplified particularly for third-world countries. In most western countries, wastes are sorted into multiple fractions including organics, recyclables, glass, metals, and combustibles [30]. In the developing countries, waste collection systems are not efficient and the collection rate is less. To tackle this issue, simplified collection methods are necessary or a boost in the form of incentives is necessary, along with adequate training/education programs on the importance of waste segregation.

Economics

The key hindrance to sustainable waste management is the economic feasibility of the waste treatment methods. Most waste management systems are not economically viable unless the government provides a

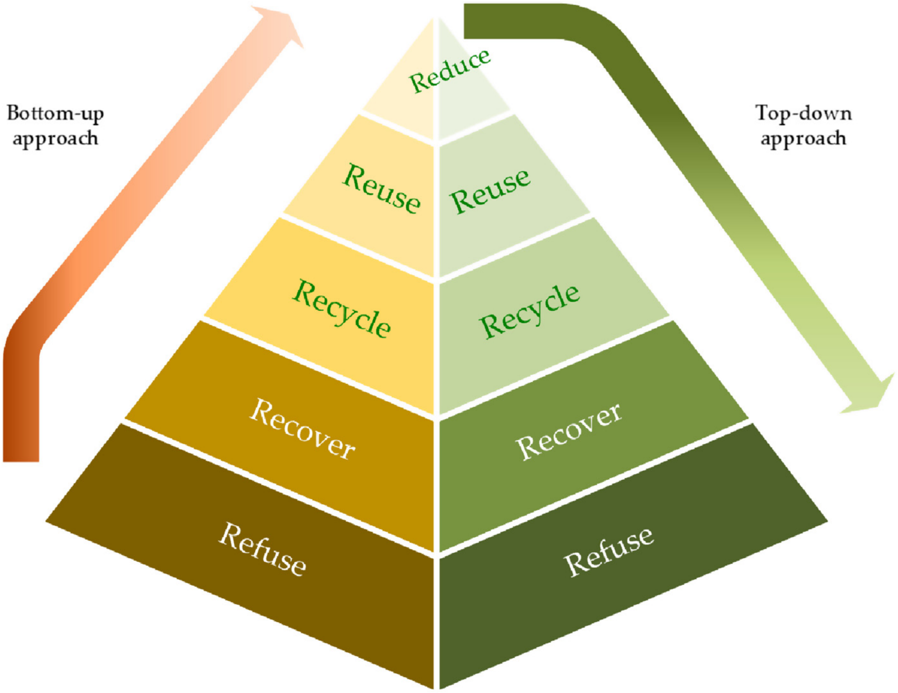

FIG. 5.5 The top-down (how it should be) versus bottom-up (how it is now) approach in a 5R waste management system.

subsidy. This is why landfilling has been preferred in developing countries rather than waste treatment and energy recovery options. Most developing countries require not only financial support to establish these technologies [6] but also a change in the business model from how conventional businesses operate.

Furthermore, the technologies need to be cost-effective for companies to operate and expand. As mentioned earlier, current waste management technologies require incentives/support systems from the government, at least in the initial phase [31]. Incentives are required in high-income countries, and for developing countries, this situation is even more challenging. Often, a change in taxation is required for the uptake of certain waste management technologies. For example, Germany provided incentives that accelerated the use of renewable energy technologies, accelerated waste management, and reduced GHG emissions [32]. If a government starts to provide tax reductions and subsidies, then private/semistate companies may be willing to enter the waste management sector. Assurances are needed in some form for companies to invest and thereby make profit in the waste management sector.

Current revenue streams in waste management systems include the polluter pays principle, producer responsibility, and gate fees for organics. This needs to be enhanced to generate further income through the selling of products. There are certain macro- and microeconomic aspects attached to this. For example, if either the crude oil price or carbon tax for fossil fuels increases, most energy recovery waste management systems may become more profitable.

Sociocultural Aspects

Waste management is also a societal issue. This is where the sociocultural aspect gains sufficient importance, equivalent to technology or economic feasibility. No waste treatment technology can be feasible unless people are willing to accept and abide by it [33]. In western countries, from an early age, children are taught how to segregate waste. When they become adults, they pass this trait on to future generations and so the tradition is carried forward. In the developing world, the awareness and education among adults is minimal, causing a significant challenge in overcoming this barrier.

Often, people have a resistance to change from their current behavior. This is one of the main facets of a sociocultural hindrance. It requires personal motivation to adhere to the change and a strong policy might provide the kick start that is required. A strong road map, alongside adequate training and awareness, is essential to overcome these barriers (Fig. 5.6).

Policy and Political Aspects

Policy is one of the key drivers that can bring all other factors to work in harmony. Good policy can drive a system. For example, Germany became the leader in the biogas industry primarily because of the policy support from the government in the form of incentives and assured tariffs. The government helped industries to innovate and reduce costs and emissions by providing additional incentives. Besides specific policies, there are other sides of political aspects that need to be considered for a sustainable waste management system. These include transparency in governance, measures to reduce corruption, etc. In developing countries, the corruption rates can be high and this is one of the reasons why there may be higher investment costs. These higher investment can costs make the technology unfeasible. More open markets and transparency in governance, along with strong policies, will help toward a transition to sustainable waste management.

FIG. 5.6 Multidimensional factors for an efficient waste management system.

CASE STUDIES

Sweden

Sweden, with 9.9 million inhabitants, has exemplified great success from a waste management perspective. Quantities of waste generated in recent years have been on the decline and recycling of materials is now common practice. Sweden is located in the cold Nordic region and thus heating is required for several months during the winter, whereas air-conditioning is necessary for shopping centers and hospitals during the summer. Consequently, energy recovery from waste is a very practical solution in Sweden. Methods include incineration (combustion) of residual waste and anaerobic digestion that can produce biogas, which can be used for electricity or, if cleaned, as a transport fuel, and digestate, a biofertilizer.

The Swedish national strategy for waste management is based on a hierarchy in which waste prevention is the first stage [34]. From 2015 to 2016, the quantity of household waste generated decreased by 11 kg per person to 467 kg household waste per person and the total quantity of household waste produced in Sweden was 4.67 million tonnes (Mt) [34]. The breakdown of treatment of household waste was as follows: 34.6% material recycling (equivalent to 1.62 Mt), 16.2% biological treatment (equivalent to 0.76 Mt), 48.5% energy recovery (equivalent to 2.26 Mt), and the remaining 0.7% sent to landfill [34]. Hence, little burden to the environment is seen through the generation of waste in Sweden. The effective utilization of waste has been possible by changing the waste production patterns, implementing corrective legislation since the 1960s and designing less material for packaging [35].

Sweden is divided into a number of municipalities for waste management. Each municipality has its own waste management strategy and regulations, and often municipalities collaborate in the development of waste management plans. It is the responsibility of the households to separate the wastes at source and follow the plans set by the municipality. Both collection of waste and waste treatment can be carried out by the municipalities or private contractors or a combination of both. Municipalities in Sweden primarily use a volume-based tariff for the collection, transport, recovery, and disposal of waste; however, a smaller proportion of municipalities operate off a weight-based tariff [36]. The money accrued by the municipality through charging customers for the collection of waste only covers the total cost of municipal waste management. In essence, the revenue will not exceed these costs. The cost on the consumer varies by location, by dwelling, and whether the household source separates food waste (which can result in lower costs). As of 2016, the average annual waste collection charge for a Swedish household was SEK 2094 and the total average annual cost in municipalities was SEK 787 per person excluding VAT [34].

The recycling of material plays a pivotal role in Sweden's plans for a sustainable society. Citizens are encouraged to separate the waste in two ways: one is by educating them about the waste and its importance and the other is by providing economic incentives. For instance, a deposit system named PANT was created to increase recycling of PET and glass bottles and aluminum cans. The customers pay a deposit of SEK 1—2 for each can or bottle and get it back when returning the bottles/cans to any shop or supermarket in Sweden. As a result of this method, more than 88% of these materials are recycled in a relatively pure form [37]. In Sweden the governmental policies were formulated to enhance the extended producer responsibility (EPR) for packaging, waste paper, refrigerators, printers, etc. The EPR shifts the responsibility to the producer to collect waste after use of a product and dispose of the waste properly [38]. The collection of packaging and paper is undertaken at recycling centers and processed to become new products. Further products for reuse are also recycled, such as plastic, glass, textiles, and construction materials. Recycling centers are available in which households can also dispose of bulky and electric waste; 580 of these centers currently exist [34]. The more the waste is separated, the more value it has and it can be easily recycled or converted into other materials or energy. Recycling centers are made convenient for the public and typically located no more than 300m from residential areas [34].

Food and residual wastes are typically separated into organic and combustible bins in Sweden, while the collection of paper and packaging is becoming more common for households. From the Swedish perspective, biological treatment of organic waste is achieved through anaerobic digestion or composting, the latter becoming less popular. For 2018, a goal has been set that for 40% of all food waste collected, both energy and nutrients, will be recovered [34]. Materials that do not fall under the category of recycling or biological treatment in Sweden are sent for energy recovery through incineration; there are 34 incineration plants in the country [34]. For 2016, 18.1 TWh of electricity was produced through energy recovery, accounting for more than any other country in Europe [34]. Additionally, Sweden imports residual waste from other countries, enhancing the country's overall fuel supply. Studies from Sweden have indicated that the separate collection of food waste can reduce incineration by reducing the collection of residual waste while simultaneously increasing recycling and biological recovery of waste, thereby offering a successful policy instrument [36]. Furthermore, valorization of food waste is common in Sweden through anaerobic digestion or food waste could potentially be used for the production of bio-based chemicals in the future [39]. Landfills are still required for wastes that do not fall under the categories of material recycling, biological treatment, and energy recovery; however, waste volumes decreased by 19% in just one year from 2015 to 2016 [34].

United States

The United States is one of the most industrialized countries in the world. The country generates a very high quantity of MSW per capita; according to the Organisation for Economic Co-operation and Development, the latest figure stands at 738 kg per person per year [40]. With a population of 319 million, the total generation of MSW in the United States was calculated in excess of 262 Mt as of 2015 [40,41]. Of this MSW, approximately 68 Mt are recycled, 2 Mt are composted, 33 Mt are combusted for energy recovery, and 137 Mt are landfilled [41]. Thus over half of all MSW generated in the United States is still sent to landfill disposal; however, this figure has reduced significantly from 94% of all MSW in the 1960s [42]. The typical makeup of MSW in the United States constitutes 29.7% containers and packaging, 20% durable goods, 20% nondurable goods, 15.1% food waste, 13.2% yard trimmings, and 1.5% other wastes. Since 1960, the generation of MSW has increased almost threefold, with a daily generation rate of 2.03 kg per person in 2015 [42].

The United States initiated its waste management measures back in 1895 in New York City. It was started with unit operations approach, control of waste management, collection and transportation, processing, incineration, and landfilling [43]. The evolution of waste management in the United States has instigated a rise in recycling, composting, and energy recovery in the recent years. However, the country can be considered to be starting from a low base, as landfilling was the dominant waste management method for decades. The tipping fee for landfills has seen an evident increase in the past 35 years in the United States. The fee has increased 2.5-fold from approximately $19 (in 1980) to $48 (in 2015), with the use of landfills declining in this period [41]. The number of active MSW landfills in the United States has decreased from approximately 7900 in 1988 to 1900 in 2009 [44]. A factor in the significant use of landfills can be attributed to the strong private sector responsible for the waste management systems in the United States, which have been somewhat resistant to change. The US Environmental Protection Agency (EPA) guidelines suggest a preferential waste treatment hierarchy that is headed by source reduction and reuse, followed by recycling/composting and energy recovery, with the least preferred option being treatment and landfill disposal [42].

Collection of household waste in the United States varies between local governments and private collectors, depending on the jurisdiction. It has been previously estimated that collection and transportation costs for waste in the United States exceeds the revenues generated from waste treatment and disposal [43]. Traditionally, households pay for waste disposal through property taxes or on a fixed fee basis. However, in some communities, pay-as-you-throw (PAYT) programs have been established. This is a variable-rate pricing system where the customer is charged based on the weight of waste they are disposing of or on a per bag basis [45]. The advantage of such an initiative is the greater incentive for household recycling and production of less waste. The benefits of recycling have been illustrated in the 2016 Recycling Economic Information study that suggested that as of 2007, recycling and reuse activities in the United States accounted for 757,000 jobs, $36.6 billion in wages, and $6.7 billion in tax revenues [41]. An example scheme is the container deposit laws set in 10 US states (California, Connecticut, Hawaii, Iowa, Maine, Massachusetts, Michigan, New York, Oregon, and Vermont), which carry deposit refund systems for beverage containers. Depending on the state, the deposit will be in the range of $0.05—$0.15. In essence, the consumer pays a deposit on the purchase of the beverage. The purpose of such a system is to shift the responsibility of packaging (and waste) to the manufacturer from the consumer. Through this, many benefits are obtained, including increased recycling rates through financial incentive and job creation.

Within the US waste management strategy is the food recovery hierarchy that includes for source reduction, food donation, animal feed, industrial use, and composting. Food waste reduction is directed at both businesses and individuals to calibrate the quantity of food that might be required, with the aim of reducing waste. The second tier of the hierarchy proposes that any nonperishable and unspoiled perishable foods can be donated to local food banks, soup kitchens, pantries, and shelter food donation [46]. Beyond this, remaining scraps can be fed to livestock as a cheaper alternative to landfill disposal. Only after these initial steps is food waste considered as a means of generating energy (fourth tier on the hierarchy). Anaerobic digestion of fats, oil, and grease is particularly befitting, as disposal of these wastes can be difficult [46]. As of 2016, there were 77 waste-to-energy facilities operating in the United States (in 22 states), with a total daily throughput of approximately 95,000 t per day [47].

Ireland (Republic of Ireland)

Ireland's waste management strategy is underpinned by the Waste Management Act 1996 and the EU Waste Framework Directive. The Directive specifies the waste management hierarchy for Ireland under which the pinnacle is the prevention of waste, followed by reuse, recycling, recovery, and disposal. Under the Waste Management Act 1996, all local authorities in Ireland must facilitate the collection of household waste in their allocated area and also provide for the provision of disposal and recovery facilities. Households typically have their waste collected once a week via private operators and it is common for operators to collect different types of wastes every other week. The collection of waste is typically a central issue in Irish policy. Under the most recent framework introduced, waste collectors can offer a range of pricing options that include for standing charges, charges per lift, charge per kilogram, charge by weight, or a combination of these options. The old structure of a flat rate charge for wastes is now being phased out for customers. Per capita, Ireland is among the highest municipal waste producers in Europe. As of 2014, Ireland had the sixth highest level of municipal waste per capita in the European Union at 586 kg, which was higher than the EU average of 474 kg per capita per year [48]. According to the latest survey available, the total quantity of waste generated in Ireland was 19.8 Mt [49].

For the purposes of future waste management planning Ireland has been split into three regions, namely, Southern Region, Eastern Midlands Region, and the Connacht Ulster Region. The national government, local government, and EPA establish how the waste management hierarchy is being achieved within these regions [50]. The Irish government typically applies the polluter pays principle in which the producer of the waste must assume the responsibility in ensuring the waste is correctly disposed of. In the past two decades, Ireland has seen an evident change in terms of its waste management strategy. This is exemplified by the avoidance of landfill, which has been directly targeted, driven by both national and EU legislations. In Ireland, only five landfills remain in operation; this is a reduction from 22 sites in 2010. From 2010 to 2019 the landfill levy increased from €30 per tonne to €75 per tonne [51].

In Ireland the MSW to be treated is described as a combination of household and commercial wastes that include dry recyclables, residual waste, food waste, and garden waste [51]. Three options are prescribed for the treatment of municipal waste: recycling, recovery through fuel production, and disposal to landfill. Latest figures suggest that as much as 79% of municipal waste is being recovered (approximately 1.94 Mt through recycling and fuel production), whereas the remainder is sent to landfill (approximately 0.54 Mt) [51]. As of 2014, Ireland had the ninth highest rate in the European Union for sending municipal waste to landfill (223 kg per capita) [48]. However, the recovery of fuel waste is expected to reduce quantities further, largely in part to a second incineration facility that became operational in 2017.

Ireland has succeeded in certain areas of waste management and a shift toward a circular economy is now the focus. For example, recovery of specific packaging wastes (cardboard, paper, glass, plastic, steel, aluminum, and wood) reached 88% and has been consistently above the targets set in this area [48]. Food waste has specifically been targeted in Ireland with regard to prevention and treatment. By 2016, the quantity of biodegradable MSW that may be sent to landfill was capped at 35% of the baseline year 1995 [52], and the 2020 target for biodegradable MSW is below 427,000 t; as of 2017, Ireland disposed of approximately 307 kt of biodegradable waste [51]. The reduction measures put in place for biodegradable waste were implemented to reduce fugitive methane emissions, a harmful GHG. Composting and anaerobic digestion are the biological treatment options available in Ireland, the latter expected to become a more sizable industry in the coming years. Currently composting is dominant and accounts for 79% of all tonnage treated [51] (Table 5.2). As of 2016, a total of 231 kt of biodegradable municipal waste is treated and this figure was reached through the introduction of productive legislation such as the Commercial Food Waste Regulations (2010) and the Household Food Waste Regulations (2013). In particular, the Commercial Food Waste Regulations (2010) required households to have a separate collection of food and biowastes and to segregate their food waste before its collection. Approximately 640,000 households in Ireland had an organic bin kerbside collection service in 2016. To achieve this, all waste collectors offered the collection service in population agglomerations of greater than 500 persons [51,53]. A trend has developed in Ireland where much

TABLE 5.2
Different Countries and Their Waste Management Activities.

Countries	GDP (USD/capita/a)	Population (millions)	MSW Generation (Mt/a)	Recycling (%)	Incineration (%)	Compost/Biological Treatment (%)	Landfilling (%)
Sweden	53,442	9.9	4.6	35	49	16	0.7
Ireland[a]	69,330	4.8	2.6	34	35	7	21
USA	59,531	325	262	26	13	9	53

GDP, gross domestic product; *MSW*, municipal solid waste.
[a] Waste export accounts for fraction of waste treatment.

of the organic bin waste collected (up to 32%) is transported to Northern Ireland for treatment in anaerobic digestion facilities [51].

Infrastructure planning is seen as a key step in Ireland's future waste management plans. The deficits in the waste management strategies have been recognized, such as the unavailability of a hazardous waste landfill and the high exportation rate of recyclable waste to other countries. However, three types of permanent facilities for the recycling of materials are available nationally. Bring banks are established for the recycling of materials such as glass bottles, aluminum cans, and unwanted clothes. Civic amenity sites are staff-run centers that open at specific hours and tend to accept much of the same wastes but with more variety, including garden wastes at specific sites. Finally, recycling centers are for the civic amenity sites (with staff and specific opening hours), typically located at local authority depots but tend to not accept very bulky items.

CONCLUSIONS AND PERSPECTIVES

Sustainable waste management practices are not limited to developing affordable technologies but beyond. A coherent intervention including various stakeholders such as government, public, industries, scientists, and nongovernmental organizations is needed to solve this problem. Waste management is a multidimensional localized problem that needs localized solutions. The important aspect of a sustainable waste management practice is the will to do it rather than passing the responsibility to other stakeholders. Several countries have successfully implemented waste management technologies and are on the verge of developing zero-waste cities. It is necessary for those countries to transfer that gained knowledge and experience to other countries for a sustainable world in the future.

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