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REVIEW

Municipal solid waste management and landfilling technologies: a review

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Abstract
The USA, China and India are the top three producers of municipal solid waste. The composition of solid wastes varies with income: low-to-middle-income population generates mainly organic wastes, whereas high-income population produces more waste paper, metals and glasses. Management of municipal solid waste includes recycling, incineration, waste-to-energy conversion, composting or landfilling. Landfilling for solid waste disposal is preferred in many municipalities globally. Landfill sites act as ecological reactors where wastes undergo physical, chemical and biological transformations. Hence, critical factors for sustainable landfilling are landfill liners, the thickness of the soil cover, leachate collection, landfill gas recovery and flaring facilities. Here, we review the impact of landfill conditions such as construction, geometry, weather, temperature, moisture, pH, biodegradable matter and hydrogeological parameters on the generation of landfill gases and leachate. Bioreactor landfills appear as the next-generation sanitary landfills, because they augment solid waste stabilization in a time-efficient manner, as a result of controlled recirculation of leachate and gases. We discuss volume reduction, resource recovery, valorization of dumped wastes, environmental protection and site reclamation toward urban development. We present the classifications and engineered iterations of landfills, operations, mechanisms and mining.

Keywords Municipal solid waste · Bioreactor landfill · Landfill leachate · Landfill gas · Landfill mining

Abbreviations

CO_2	Carbon dioxide
CO	Carbon monoxide
$/toe	Dollars per tonne of oil equivalent
$/ton	Dollars per tonnes
FAO	Food and Agricultural Organization
GJ	Gigajoules
HID Global	Hughes identification devices
H_2	Hydrogen
H_2S	Hydrogen sulfide
kcal/kg	Kilocalorie per kilogram
kg/capita/day	Kilogram per capita per day
kg	Kilogram
km	Kilometer
kWh/m^3	Kilowatt hour per cubic meter
kWh	Kilowatt hour
MW	Megawatt
M	Meter
CH_4	Methane
mg/L	Milligram per liter
mV	Millivolts
MSW	Municipal solid waste
N_2	Nitrogen
OECD	Organisation for Economic Co-operation and Development
O_2	Oxygen
Pa	Pascal
PAYT	Pay as you throw
%	Percentage
pH	Potential of hydrogen
t.km	Tonne-kilometer
tonnes/day	Tonnes per day
USEPA	United States Environmental Protection Agency
vol.%	Volume percent
wt%	Weight percent

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Introduction

The high consumption rates for energy and goods matched with the escalating population growth and high standards of living lead to the high levels of the municipal solid waste generation that pose serious threats to the environment if not disposed of or recycled effectively. Municipal solid waste is the assorted mixture of solid wastes discarded by the urban and rural population daily as garbage, thrash and refuse. Currently, an estimated 2 billion tonnes of municipal solid waste is generated globally, out of which almost 33% remain uncollected by municipalities (Waste Atlas 2018). Approximately, an average of 0.74 kg of waste is generated per capita per day (Waste Atlas 2018). According to the World Bank, the generation of municipal solid waste is anticipated to rise to 3.4 billion tonnes by 2050 (The World Bank 2020a). From the total municipal solid waste that is collected by the municipalities, about 70% ends up in landfills and dumpsites, 19% is recycled and 11% is used for energy recovery. From the current world population of 7.6 billion (US Census Bureau 2020), nearly 3.5 billion people are deprived of basic waste management facilities (Waste Atlas 2018). It is also foreseeable that the number of people without proper access to elementary waste management services could reach 5.6 billion by 2050.

Municipal solid waste originates as the solid wastes of a municipality collected from households, offices, small-scale institutions and commercial enterprises. Municipal solid waste varies substantially in its composition and classification between different municipalities worldwide, although it consists of both biodegradable and non-biodegradable fractions from organic and inorganic materials, respectively. Nevertheless, municipal solid waste typically consists of kitchen waste, yard waste, paper and cardboard, plastic and rubber, metal, glass, electronic waste, inert materials and miscellaneous thrash (Table 1). The kitchen waste and yard

Table 1 Typical composition of municipal solid waste by component type

Kitchen waste	Food waste, e.g., spoiled meat, fish, bones, eggshells, crab, mussel and lobster shells and expired solid food Agro-food residues, e.g., vegetable refuse, fruit shells, corncob, husk, kernels, peels, rind, seeds Coffee residues and waste tea leaves
Yard waste	Leaves, grass, tree trimmings, twigs, bark, straw, stalks, charred wood
Paper and cardboard	Newsprint, advertisement flyers, magazines, books, tissue paper, parchment paper, thermal paper, copy paper, multiuse paper, shredded office paper, folders, paper bags, cardboard boxes, packaging boxes, corrugated fiberboard
Plastic and rubber	Low-density polyethylene (e.g., shampoo bottles, detergent bottles, edible oil containers and plastic cans) High-density polyethylene (three-dimensional printer filament, bottle caps, coax cable insulation, electrical plumbing boxes, food storage containers, shoe last, plastic lumber, piping for water and sewer, plastic surgery and storage sheds) Polypropylene (bottles, chairs and desks) Polyethylene terephthalate (e.g., potable water bottle and beverage bottles) Polyethylene (e.g., low-grade polythene bags, plastic packaging) Polycarbonate (water and milk packaging bottles/cans, compact disks, digital versatile disks and safety goggles) Polyvinyl chloride (e.g., vinyl records, wire rope, construction flooring, ceiling tiles, home playground, foam and toys) Polystyrene (e.g., flexible plastics, plastic cups) Clear warp; ziplock bags; rubber bands
Metal	Food packaging cans, cans, aluminum foil, cookware, metal utensils and culinary equipment, knives, wires, fences, bottles, lids
Glass	Food storage containers, glass bottles, casserole dish, utensils, light bulbs, home décor, decorative and framed mirrors
Electronic waste	Dead batteries Electronic devices (e.g., thrashed computers, monitors, laptops, tablets, mobile phones, sound systems, clock and watches)
Miscellaneous	Ceramics Discarded clothes Rags (e.g., torn bags, tote and luggage) Biomedical wastes (e.g., needles, syringe and broken household health devices) Pharmaceuticals (e.g., medicine, pills, capsules, creams and cosmetics products) Diapers; sanitary napkins; contraception Pet litter Leather and textiles Carpet
Inert materials	Broken and discarded furniture Stones, soil, silt, concrete, ash, dust, drywall and other inorganic materials Construction, demolition and renovation wastes

The items listed in this table are a general representation of municipal solid wastes. The composition, categorization and classification of municipal solid wastes are subject to some disparity from cities to countries depending on local jurisdiction and solid waste designation wastes together comprise the organic fraction of municipal solid waste. Among all the components of municipal solid waste, the miscellaneous garbage is the most heterogeneous, which includes textiles, fabrics, biomedical wastes (e.g., sharps and glasses), personal hygiene products, health care items, cosmetics, pharmaceuticals, pet litter, leather, rubber and polymeric residues.

Similar to its composition, management practices for municipal solid waste differ within municipalities, cities, states and countries. However, the basic stages in the management of municipal solid waste are: (1) generation of wastes; (2) collection, handling and transfer of waste; and (3) disposal, processing and treatment of waste. Table 2 summarizes the sequential steps involved in each stage of the municipal solid waste management system in developed and developing countries. The management of municipal solid waste has always been a paradigm between developing and developed countries. It is important to note that the efficient management of municipal solid waste, i.e., disposal, diversion or recycling, largely depends on the population and gross national income of a country. In developed countries, the waste-to-energy technologies for municipal solid waste conversion to fuels, heat and power are well established (Moya et al. 2017; Nanda and Berruti 2020). On the other hand, the developing countries where the population density demands an available capacity for landfilling still strive to manage effectively and hygienically the collection, transport and disposal of municipal solid waste. Population density, socio-economic aspects, cultural facets, average living standards, unplanned management and lack of stringent environmental policies usually impede adequate remediation of municipal solid waste in developing countries. The United Nations has categorized the effective management of municipal solid waste under two sustainable development goals such as goal 11, i.e., sustainable cities and communities, and goal 12, i.e., responsible consumption and production (United Nations 2020).

Municipal solid waste is a renewable and economical resource that has high potentials to recover energy and valuable resources through waste-to-energy or energy-from-waste conversion and other valorization techniques. Different waste-to-energy technologies including thermochemical and biological conversion technologies are available to convert municipal solid waste into solid, liquid and gaseous fuels to supplement the magnifying energy demands. While incineration is the most preferred waste-to-energy technique dealing with the combustion or burning of municipal solid waste to generate energy, steam as well as combined heat and power, it also significantly reduces the volume of the wastes. Incineration can reduce the weight and volume

Table 2 Sequential steps in a classical municipal solid waste management system in developed and developing countries

Generation of municipal solid waste at the source	Generation of wastes in households, offices, institutions and commercial enterprises The solid waste stream usually includes kitchen waste, yard waste, paper and cardboard, plastic and rubber, metal, glass, electronic waste, inert materials and miscellaneous thrash Municipal solid waste in developed countries contains a higher fraction of plastic and paper waste with low moisture content and high heating value Municipal solid waste in developing countries contains a higher fraction of organic matter with high moisture content and low heating value The proportion of inorganic components in the waste stream depends on the country's gross national income
Collection, handling and transfer of municipal solid waste	Segregation and sorting of solid wastes at the source is satisfactory in developed countries but is typically low or not practiced in developing countries In some developing countries and third-world countries, the scheduled collection of municipal solid waste by the municipalities is poor or not practiced, which leads to open dumping In developed countries, the garbage collection truck/vehicle arranged by the local municipality collects the solid waste from households and designated areas The waste transfer stations are found in most metropolitan cities
Disposal, processing and treatment of municipal solid waste	In most developing countries and some highly dense developed countries, incineration is practiced for municipal solid waste volume reduction and heat and power generation Landfilling is the most preferred solid waste disposal method in developed countries In most developing countries where low- and middle-income groups are prevalent, open dumping of municipal solid waste prevails due to a lack of efficient waste management facilities and limited availability of sanitary landfills Implementation of waste-to-energy recycling processes such as pyrolysis, liquefaction, gasification and anaerobic digestion can produce specific green fuels such as bio-oil, producer gas, synthesis gas, methane, hydrogen and biochar

of municipal solid waste by 80–85 wt% and 95–96 vol.%, respectively (RenoSam and Rambøll 2006). On the other hand, pyrolysis (Fang et al. 2018), liquefaction (Katakojwala et al. 2020) and gasification (Nanda et al. 2016c; Munir et al. 2019; Saidi et al. 2020) are some of the well-known thermochemical techniques that can be applied for municipal solid waste conversion to bio-oil, syngas and char products. Municipal solid waste can be converted to biogas or biomethane and fertile compost through respective biological conversion technologies such as anaerobic digestion (Jain et al. 2015; Singh et al. 2020a, b) and aerobic composting (Shah et al. 2019).

At a global scale, only a quarter of the municipal solid waste collected is diverted to waste management options such as recycling, anaerobic digestion and composting. Therefore, it is imperative to determine the effective way for the disposal or treatment of municipal solid waste around the world as the waste recycling patterns and practices differ between countries. Landfilling is a traditional practice used for the burial of non-recyclable wastes around the world, although in some developing countries the waste is disposed in piles or thrown into pits rather than concealing with soil. Landfilling appears to be a common organized municipal solid waste disposal procedure in most developed countries but is relatively less popular in developing countries that have limitations of open space due to high population density. In developing countries, some landfill sites also serve as temporary waste storage and have containment facilities for waste consolidation, transfer and processing such as sorting, recycling and treatment. Landfills can also act as specific sites for municipal solid waste disposal that can be monitored for waste processing and sorting of recyclable materials before tipping.

Even though landfills are the most preferred method for municipal solid waste disposal, the lack of space for new landfills in highly metropolitan cities and developing countries is leading to the implementation of waste-to-energy options for recycling municipal solid waste. Moreover, the current state of landfill treatment is mature and largely limited to dumping in pits with soil concealing. With this objective, the current status of landfill technologies has been evaluated to identify the opportunities, challenges and barriers to effective implementation and sustainable management practices for municipal solid waste. This paper also reviews bioreactor landfill technology as a new iteration to the conventional landfilling. An attempt has been made to provide the recent advancements in the utilization of landfill leachate and upgrading of landfill gas to energy and fuels. Landfill mining and reclamation as a new concept to enhance the material recycling and energy recovery from closed landfills is discussed with its advantages, limitations and uncertainties. The paper also makes a widespread discussion on the domestic and international statistics of municipal solid waste generation, composition, management, disposal and diversion. Besides, the strengths, weaknesses, opportunities and threats relating to the disposal and management practices for municipal solid waste have been discussed.

Management of municipal solid waste at a global scenario

Figure 1 illustrates the worldwide trend of municipal solid waste generation. Currently, the top three municipal solid-waste-generating countries are the USA, i.e., 258 million metric tons, China, i.e., 220 million metric tons, and India, i.e., 169 million metric tons. Five developing countries, namely China, India, Brazil, Indonesia and Mexico, are among the top ten municipal solid-waste-generating nations because of significant urban populations that are rapidly prospering and adopting high-consumption lifestyles similar to developed countries. Developed countries tend to generate much higher quantities of municipal solid waste per capita than the developing and third-world countries because the waste generation rate is contingent on a nation's economic and social prosperity.

Canada ranks seventeen in the list of countries with the maximum generation of municipal solid waste. Canada has a current output rate of 49,616 tonnes/day of municipal solid waste compared to its leading opponent, i.e., the USA (624,700 tonnes/day) (Hoornweg and Bhada-Tata 2012). However, Canada ranks second in the list of top municipal solid-waste-generating countries with its current output rate of 2.33 kg/capita/day as opposed to the USA, i.e., 2.58 kg/

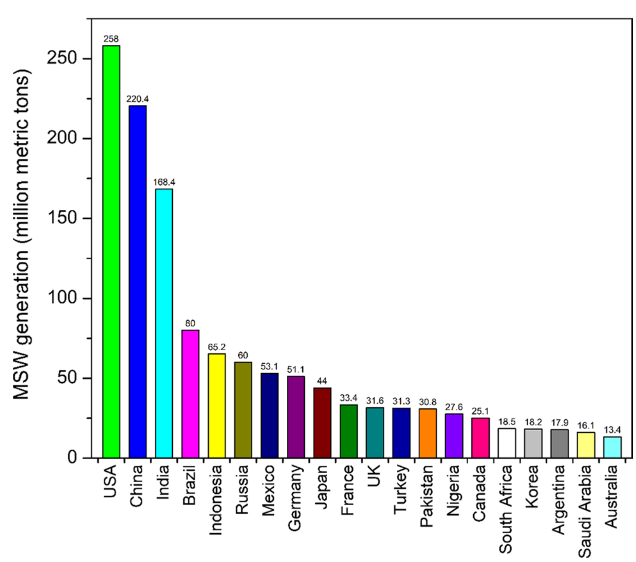

Fig. 1 Worldwide generation of municipal solid waste. It should be noted that the top five solid-waste-generating countries are the USA, China, India, Brazil and Indonesia. (Data source: Statista 2020)

capita/day. The current population of Canada is 37.8 million, which includes 81% of its urban population (Worldometers 2020). On the other hand, the current population of the USA is 331 million, which includes 83% of its urban population. Although there is a big difference in the total population of both countries, their urban population is almost equivalent. Therefore, both the USA and Canada have almost analogous per capita generation of municipal solid waste. The greater population density in the urban areas and high standards of living in these two North American countries tend to make them the leaders in per capita generation of municipal solid waste.

China is believed to lead the world with its highest municipal solid waste production of 1,397,755 tonnes/day by 2025, followed by India, i.e., 376,639 tonnes/day, and Brazil, i.e., 330,960 tonnes/day as shown in Table 3 (Hoornweg and Bhada-Tata 2012). It is envisaged that most developing Asian countries would soon match or surpass their rates of the municipal solid waste generation with that of developed countries. A report suggests that China has landfilled over 3 billion tonnes of municipal solid waste in the last three decades and is currently disposing of approximately 73% of its wastes in 547 operational urban landfills (Zhou et al. 2015). In India, nearly 150 million tonnes of municipal solid

Table 3 Current and projected generation of municipal solid waste worldwide

Country	Current generation (kg/capita/day)	Current generation (tonnes/day)[a]	Projected (2025) generation (kg/capita/day)	Projected (2025) generation (tonnes/day)
USA	2.58	624,700	2.30	701,709
China	1.02	520,548	1.70	1,397,755
Brazil	1.03	149,096	1.60	330,960
Japan	1.71	144,466	1.70	146,982
Germany	2.11	127,816	2.05	126,633
India	0.34	109,589	0.70	376,639
Russia	0.93	100,027	1.25	120,076
Mexico	1.24	99,014	1.75	–
UK	1.79	97,342	1.85	110,515
France	1.92	90,493	2.00	107,318
Italy	2.23	89,096	2.05	86,520
Turkey	1.77	86,301	2.00	135,962
Spain	2.13	72,137	2.10	78,926
Indonesia	0.52	61,644	0.85	151,921
South Africa	2.00	53,425	2.00	72,146
Pakistan	0.84	50,438	1.05	109,244
Canada	2.33	49,616	2.20	69,179
South Korea	1.24	48,397	1.40	58,496
Argentina	1.22	41,096	1.85	80,420
Nigeria	0.56	40,959	0.80	101,307
Egypt	1.37	40,822	1.80	83,583
Thailand	1.76	39,452	1.95	56,673
Australia	2.23	36,164	2.10	46,759
Vietnam	1.46	35,068	1.80	72,909
Philippines	0.50	29,315	0.90	77,776
Netherlands	2.12	27,945	2.10	31,206
Columbia	0.95	27,918	1.50	66,269
Venezuela	1.14	25,507	1.50	51,089
Algeria	1.21	23,288	1.45	46,078
Morocco	1.46	23,014	1.85	44,389
Malaysia	1.52	21,918	1.90	51,655
Poland	0.88	20,630	1.20	27,883
Saudi Arabia	1.30	20,000	1.70	50,424

Reference: Hoornweg and Bhada-Tata (2012)

[a]This column has been filtered to show countries with the current municipal solid waste generation $\geq$ 20,000 tonnes/day

waste generated is disposed of in landfills covering more than 60,000 hectares of land (Mohan et al. 2016).

Owing to globalization, the developing countries are swiftly adopting the lifestyle of developed countries leading to considerable quantities of municipal solid waste generation. In terms of the current per capita output of municipal solid waste, the top ten nations are the USA, Canada, Australia, Italy, Spain, the Netherlands, Germany, South Africa, France and the UK (Hoornweg and Bhada-Tata 2012). Furthermore, it is projected that most of these countries would still be dominant concerning their per capita output of municipal solid waste. This can be explained in terms of the consumption behavior of the city dwellers in these countries. The urban population produces more municipal solid waste than rural communities because of the difference in food habits, resource consumption patterns, lifestyle and living standards.

The primary threat to poor management of municipal solid waste is often reflected in public health. The urban poor or the people categorized to be below the poverty line are severely affected by unsustainably managed wastes. In most middle-income countries and third-world nations, municipal solid waste is often disposed of in unregulated dumps, roadsides and open areas for natural decomposition or open burning. These untenable practices lead to severe health hazards, safety concerns, unsanitary conditions and pollution problems. The unsanitary conditions and poorly managed municipal solid waste could lead to several problems, such as (i) breeding of insects, flies, pests and disease vectors; (ii) greenhouse gas emissions by methane generation; (iii) putrid leachate runoff; and (iv) social unrest by the nauseating odor in the neighborhood.

To cope with the unprecedented generation of municipal solid waste on a global scale, The World Bank strategically finances and advises on many waste management projects (The World Bank 2019). One of the prime interests of The World Bank is to build or refurbish self-contained infrastructures for waste sorting and treatment, construct landfills and transfer stations, and supply garbage collection bins, dumpsters, waste collection trucks to municipalities. Social awareness and advising the rural and urban populations on functional waste systems (e.g., waste reduction and source separation), policy measures, behavior changes and social responsibilities are some of the chief mandates of The World Bank.

Figure 2 depicts the current and projected scenarios of municipal solid waste generation by the global population classified under different income levels. According to The World Bank, low-income and high-income countries are defined as those with a per capita gross national income ≤ $1025 and gross national income ≥ $12,376 as of 2020 fiscal year (The World Bank 2020b). Conversely, lower-middle-income and upper-middle-income nations are those with a per capita gross national income of $1026–$3995 and $3996–$12,375, respectively. At present, high-income countries produce maximum per capita of municipal solid waste, i.e., 1,649,547 tonnes/day compared to low-income countries that generate minimum per capita of municipal solid waste, i.e., 204,802 tonnes/day (Fig. 2a). The total municipal solid waste generation in lower-middle-income countries, i.e., 1,012,321 tonnes/day, is relatively higher than that of upper-middle-income countries, i.e., 655,586 tonnes/day, because of the inclusion of highly populous countries like India, Indonesia, Pakistan and Nigeria in the lower-middle-income group of nations. These lower-middle-income countries are also among the

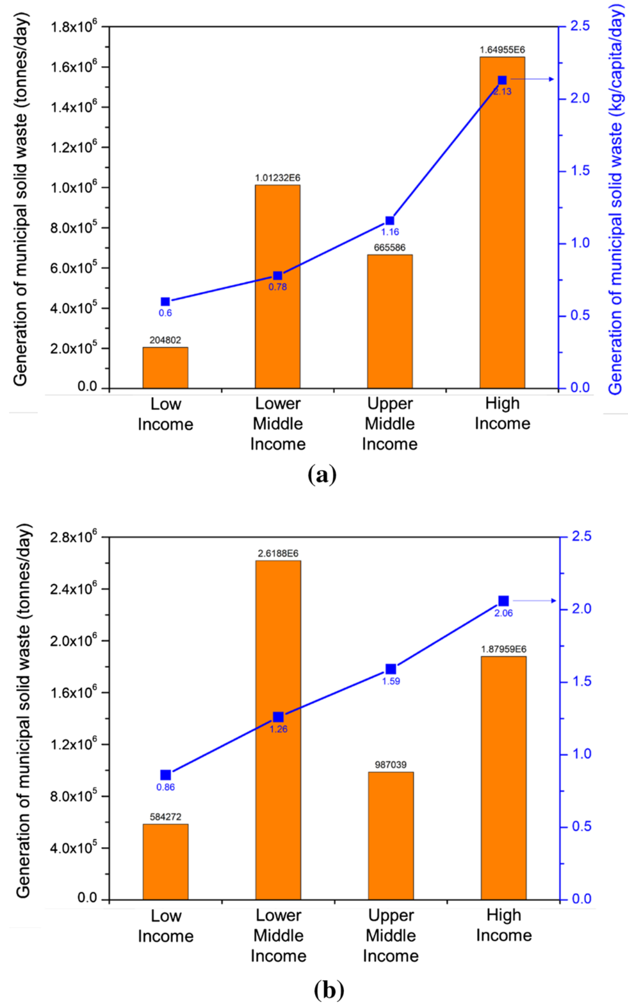

Fig. 2 Worldwide generation of municipal solid waste by population of different income levels. **a** Current estimates, **b** projected 2025 estimates (Data source: Hoornweg and Bhada-Tata 2012). As per the current estimates, the high income level generates maximum municipal solid waste, i.e., 2.1 kg/capita/day, followed by the upper middle income level, i.e., 1.2 kg/capita/day. It is expected that municipal solid waste generation by lower middle income level can double by 2025

top 20 municipal solid waste producers (Hoornweg and Bhada-Tata 2012). Rapidly developing countries such as India and China have very high urban per capita municipal solid waste generation rates as they have large relatively poor rural populations (low-income group) that tend to dilute the national estimates.

Similar to the per capita generation of municipal solid waste, its composition also varies among different income groups across the world. Owing to the heterogeneous nature of municipal solid waste, its physicochemical characteristics and composition vary significantly across countries and even cities within a country. The composition of municipal solid waste in various income groups is shown in Fig. 3. The physical composition and characteristics of municipal solid waste depend upon various factors such as socio-economic profile, local climatic conditions, demographics, the extent of recycling and municipal solid waste collection frequency. The low-income group demonstrates a high proportion of organic waste composition, whereas the high-income group shows a relatively greater generation of waste paper, metals, glasses and miscellaneous garbage. Both middle- and high-income groups also have high plastic wastes. Municipal solid waste collected from rural areas is characterized by about 40–85% of organic matter (Worldwatch Institute 2012). Similarly, organic matter in municipal solid waste from low-income population groups can account for up to 65%, but only a quarter in the case of the high-income group (Baker 2012). Instead, the organic matter content in municipal solid waste is usually below 30 wt% in developed countries, whereas in developing countries, it is more than 50% (Aleluia and Ferrão 2016).

The heating value of municipal solid waste from developing countries is much lower due to the large organic matter load and the high amount of moisture in it. For instance, the representative calorific value of arbitrary municipal solid waste in a few developing countries is as follows: Bangladesh (717 kcal/kg), India (800–1100 kcal/kg), Sri Lanka (950–1250 kcal/kg), Thailand (500–1500 kcal/kg), China (1200–1600 kcal/kg) and Malaysia (1500–2600 kcal/kg) (Kumar and Samadder 2017). In contrast, developed countries characteristically generate a large amount of plastic-based and paper wastes, which contribute to the comparatively higher heating value of the municipal solid waste due to lower moisture content and greater carbon content. For example, the calorific values of municipal solid waste generated in a few developed countries are Japan (2000–2200 kcal/kg), the UK (2200–3000 kcal/kg) and South Korea (2600–3000 kcal/kg) (Kumar and Samadder 2017). The share of inorganic components in municipal solid waste rises with the increase in a nation's gross national income.

Food wastes constitute a significant portion of the high moisture containing the organic fraction of municipal solid waste from developing countries. According to the Food and Agricultural Organization, currently 1.3 billion tonnes of food waste is generated across the world every year, the carbon footprint of which estimates to 3.3 billion tonnes of CO_2 equivalent (FAO 2020). Considerable amounts of food wastes are found in municipal solid waste due to several reasons such as (1) overproduction; (2) physical damage to fruits and vegetables during harvesting, transportation and storage; (3) rotting caused by microorganisms, insects and pests; (4) exclusion of naturally impaired fruits and vegetables by supermarkets; and (5) consumer behavior of irresistible purchase versus consumption (Nanda et al. 2016c; Okolie et al. 2020). Conversely, developed countries are economically benefited by a large amount of waste paper, plastic, metals and glass in their municipal solid waste stream because the global market for recycling waste paper and scrap metal is more than $30 billion per year (Worldwatch Institute 2012).

From these demographics, it is clear that the rapidly escalating global population and high standards of urban lifestyle generate massive amounts of solid wastes because of the unparalleled consumption of energy and goods. Despite several opportunities, the municipalities in both developed and developing countries face many challenges to effectively manage solid wastes for disposal (i.e., landfilling), recycling or diversion (i.e., waste-to-energy conversion or alterative usage). Special emphasis should be laid upon the promising scenarios of efficient management of municipal solid waste in terms of its recycling, energy and resource recovery as

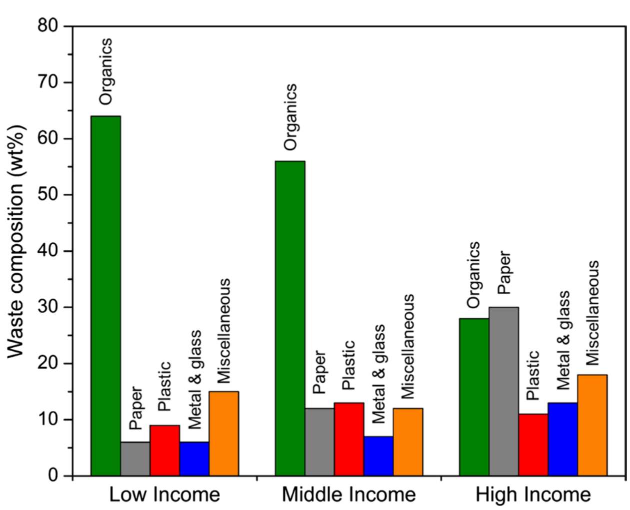

Fig. 3 Typical composition of municipal solid waste among various income levels (Data source: Kumar and Samadder 2017). The organic wastes are higher in the case of low- and middle-income groups, whereas waste paper, metals and glasses are greater in the high-income groups. In contrast, plastic wastes are generated in higher amounts in the middle-income groups

well as sustainable landfilling. Landfilling of solid wastes can be sustainable when landfills are designed, iterated, operated and maintained considering some significant factors such as (1) regulatory protocols, (2) worker safety, (3) lower environmental impacts, (4) recovery and upgrading of landfill leachate and gases and (5) possibility for mining.

Landfill technology

Landfilling is the procedure of organized disposal of biodegradable and non-biodegradable wastes in a designated terrestrial burial site or landfill, which is located away from a municipality's suburban areas. Landfilling has been a conventional and most lucrative waste disposal route followed in many countries. While incineration demands big investments for extensive infrastructures and extremely high temperatures, the resource recovery technologies, e.g., pyrolysis, liquefaction, gasification, anaerobic digestion and composting, also require intensive labor and costs relating to equipment operation and maintenance. Landfilling is advantageous over incineration and recycling of municipal solid waste because of its cost-effectiveness and less labor-intensive procedures. Moreover, a consolidated landfilling can also generate revenues through the utilization of its landfill gas and leachate for its energy generation. Figure 4 graphically illustrates the integration of a landfill with leachate recycling and upgrading of landfill gas to biogas followed by its combustion or flare to generate combined heat and power.

The number of active and closed landfills in the European Union is between 150,000 and 500,000, which serves as the storehouse for massive amounts of municipal solid waste generated in Europe (Jones et al. 2013). In particular, more than 150,000 landfills in Europe contain 30–50 billion cubic meters of municipal solid waste (Wagner and Raymond 2015). In the USA, over 33 million tonnes of municipal solid waste is incinerated and more than 136 million tonnes of municipal solid waste is landfilled every year (USEPA 2016). However, landfilling of municipal solid waste declined from 89% in 1980 to less than 53% in 2014 in the USA due to the advancements made in recycling, composting, incineration and energy recovery technologies. Some estimates show that both the USA (Peters 2016) and Canada (Giroux 2014) individually have more than 2000 active landfills to dispose of their municipal solid waste, whereas Canada has more than 2000. In Canada, every year nearly 97% of the residual solid wastes after diversion, i.e., recycling and composting as well as energy recovery, are landfilled, which approximates to 24 million tonnes (Giroux 2014). Around 60% of the municipal solid waste generated in the Organisation for Economic Co-operation and Development or OECD countries is also landfilled (Hoornweg and Bhada-Tata 2012). These landfills can also be transformed from being "waste storehouses" to "energy powerhouses" with the implementation of efficient integrated technologies to deliver green energy and secondary materials.

Figure 5 illustrates the share of energy input in landfilling and incineration of municipal solid waste. According to Nabavi-Pelesaraei et al. (2017), both landfilling and incineration of wastes require relatively less human labor when compared to other major energy inputs through diesel, electricity and transportation. In a recent techno-economic analysis and lifecycle assessment studies of 8500 tonnes of municipal solid waste in Tehran, Iran, it was determined that incineration necessitated a higher fraction of electricity, i.e., 41% of the total energy input when compared to landfilling

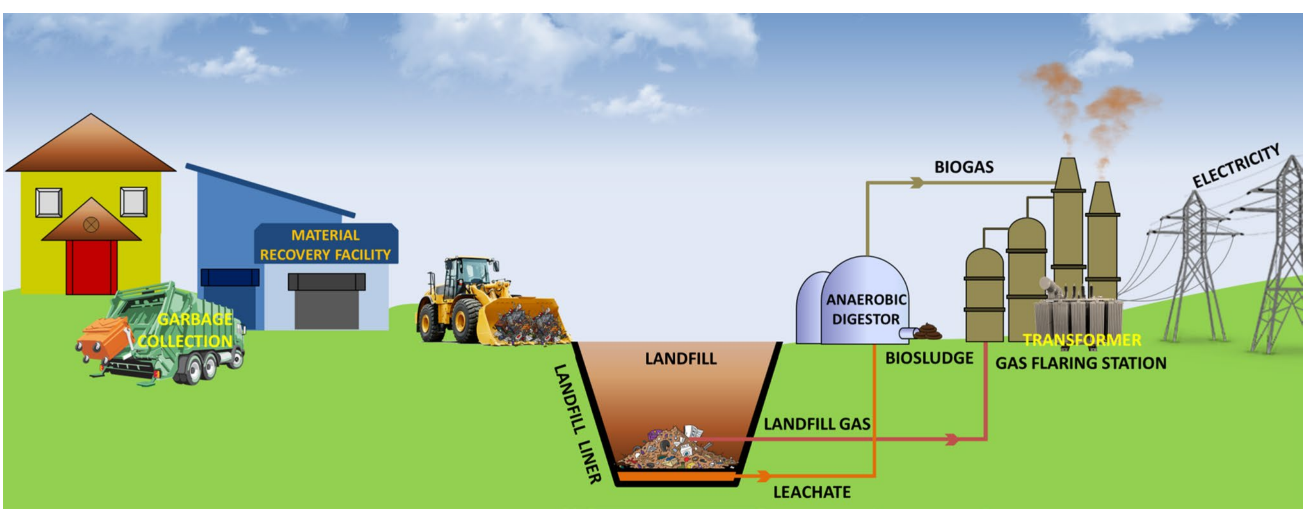

Fig. 4 Consolidated municipal solid waste landfilling system and utilization of leachate and landfill gas for energy generation. Such an integrated waste management and waste-to-energy generation approach can aid in the sustainable management of domestic wastes while securing clean energy demands

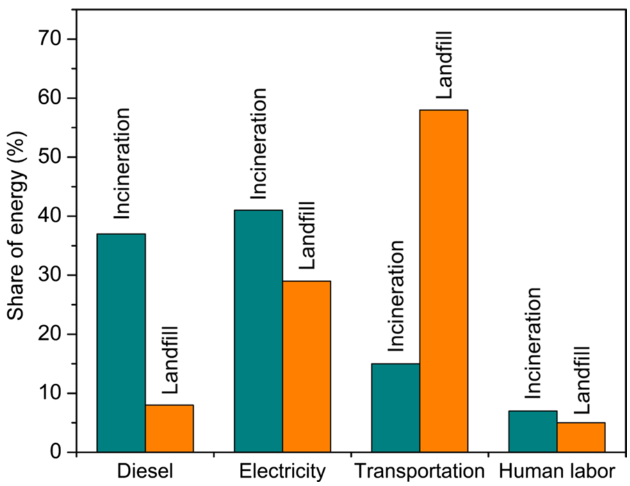

Fig. 5 Share of energy inputs in landfill and incineration (Data source: Nabavi-Pelesaraei et al. 2017). Landfilling and incineration of municipal solid wastes necessitate comparatively less human labor in contrast to major energy inputs through diesel, electricity and transportation

that requires 29% of electricity (Nabavi-Pelesaraei et al. 2017). More precisely, incineration of 8500 tonnes of municipal solid waste required the input of 422.2 kWh of electricity with an output of 3827.3 kWh. In other words, for every 1.99 tonnes of municipal solid waste incinerated for electricity generation, nearly 1 GJ of energy is consumed, although more efficient methods and systems could enhance the energy output rate. Secondly, energy investment attributed through transportation shares a major portion by landfilling, i.e., 21,600 t.km or 58% of the total energy input than by incineration, i.e., 391.2 t.km or 15% of the total energy input. Using fuel-efficient garbage collection trucks or trucks with higher garbage collection volume or in-built equipment for garage compaction, the selection of shorter distances can reduce the energy consumption incurred via the transportation sector in landfilling.

Government authorities worldwide usually regulate the management of landfills. A few examples of developed countries that have stringent rules on landfilling include Canada (i.e., provincial environmental agencies and Environmental Protection Acts, EPA); the USA (i.e., state environmental agencies and the US Environmental protection Agency, USEPA); the UK (i.e., Landfill Allowance Trading Scheme); Scotland (i.e., Scottish Environmental Protection Agency); Northern Ireland (i.e., Northern Ireland Environmental Agency); and the European Union (i.e., Landfill Directive). In some metropolitan cities in developing countries, open-air, uncontrolled and poorly managed dumping of municipal solid waste is commonly practiced which raises many environmental concerns. In some municipalities, more than 90% of municipal solid waste is directly disposed of in landfills with substandard management, which leads to unsanitary conditions. In most developing countries, no segregation of municipal solid waste at the source takes place. As a result, all of the wastes including infectious biomedical wastes from healthcare clinics and hospitals as well as toxic industrial residues end up at the landfill disposal site.

The location of landfills and remediation facilities vary according to the type of wastes, e.g., household waste, toxic chemicals, biohazards, biomedical wastes, radioactive wastes as well as construction, demolition and renovation wastes. Based on the waste refuse, landfills can be classified into different categories such as Class 1, i.e., soil disposal; Class 2, i.e., disposal of minerals as well as construction, demolition and renovation waste; Class 3, i.e., municipal solid waste disposal; Class 4, i.e., commercial and industrial waste disposal; Class 5, i.e., hazardous waste disposal; and Class 6, i.e., underground disposal of hazardous wastes (Ehrig et al. 2011). Another classification of landfills is based on the type of its functionality such as secure landfill, monofill landfill, reusable landfill and bioreactor landfill (Reinhart and Townsend 1998). The secure landfills entomb the wastes to postpone the adverse environmental impacts, whereas the monofill landfills accommodate the wastes that cannot be processed through incineration, resource recovery and composting. On the other hand, reusable landfills allow the stabilization of wastes for a longer period followed by excavation to recover metals, glass, plastics and compost. Last but not the least, bioreactor landfills are the engineered sanitary landfills equipped with liners and leachate collection and recirculation systems to optimize microbe-assisted waste degradation while minimizing the environmental impacts (Jayasinghe et al. 2014).

Landfills can be classified into open dump landfills, semi-controlled landfills and sanitary landfills (Narayana 2009). An open dump landfill is a land area where the municipal solid waste wastes are disposed of in an open environment with air contact. Open dump landfills are commonly found in all developing countries where the municipal solid waste refuses are dumped arbitrarily into low-lying open areas. Since these landfills are poorly managed, they turn into a niche for scavengers, e.g., falcons, eagles, vultures, crows and other birds as well as flies, mosquitoes, pests, worms, rodents and pathogenic microorganisms. However, these operational issues are eliminated in anaerobic digestion because of oxygen-deficient conditions. Neighborhood residential complaints relating to persistent foul odor from the open dump landfill areas are quite common. Regulatory laws in many developed countries prohibit open dumping by considering it illegal. Although 79% of municipal solid waste is landfilled in Canada (Kelleher et al. 2005), the Ministry of Environment and Climate Change implement strict regulations on waste disposal and illegal dumping which may result in penalties, legal investigation and prosecution (Government of Ontario 2020). Furthermore, the US Environmental Protection Agency prohibits open dumping of thrash by law along with the issuance of Administrative Citation and penalty of US $1500–3000 for littering, scavenging, open burning and proscribed disposal of (bio)hazardous wastes as well as construction, demolition and renovation waste on open land or flowing water (Illinois Environmental Protection Agency 2020).

Semi-controlled landfills are operated landfills that are located in designated dumpsites where municipal solid waste refuse is sorted on-site, shredded and compacted before disposal. The disposed of piles of thrash are crushed and leveled with bulldozers or crawlers and covered with a layer of topsoil daily to prevent nuisances such as breeding of scavenging birds, animals, pests and microorganisms. Although the semi-controlled landfills are relatively less malodorous due to topsoil cover, they are not engineered to manage the landfill gas emission and leachate discharge (Narayana 2009). On the other hand, sanitary landfills are advanced varieties of semi-controlled landfills. In addition to on-site solid waste sorting, segregation, size reduction, densification and topsoil covering, the sanitary landfills also have engineered facilities to collect liquid leachate and landfill gas emissions. Properly defined within a regional boundary away from the residential areas, sanitary landfills are characterized with a routine placement of cover soil on top of freshly disposed of wastes, which minimizes odor, disease vectors, fires and waste scavenging. These types of landfills are common in developed countries with facilities for interception and treatment of the leachate. Sanitary landfills are also planned for landscape expansion by digging new dumpsites after capping the existing ones subject to saturation.

Landfill design and operation

The efficient landfilling of wastes is critical to prevent the seepage of landfill gases leading to potential fire hazards and long-term global warming due to a high concentration of methane and drainage of leachate causing chronic groundwater pollution. Therefore, the architecture of an engineered sanitary landfill in terms of its design and operation is significant in mitigating the impacts of municipal solid waste disposal on the environment, especially to the groundwater and air quality. The critical components of designing a modern landfill are landfill foundation, liner, barrier cap, leachate collection system, landfill gas collection station, gas flare station and soil cover (Fig. 6).

The moisture contained in the municipal solid waste, rainfall and snowfall (limited geographically) results in the production of leachate from landfills that are rich in toxic chemicals, dissolved organics and suspended solid particles. The robustness of the landfill foundation and liner could prevent their release into the groundwater. The leakage of municipal solid waste leachate also depends on the relative permeability of landfill liner. A landfill liner is laid down under an engineered sanitary landfill to act as a low-permeable barrier. Since it is practically difficult to replace the liners of older landfills, it is recommended to utilize impermeable liners, e.g., compacted clay or geosynthetic materials for newer landfills (Narayana 2009). The earthen materials such as soil and clay need to reach their target hydraulic conductivity requirements for use as a liner (Townsend et al. 2015). Engineered landfills are constructed with a bottom layer of compacted clay having a thickness sufficient to allow hydraulic pressure, which is blanketed by high-density polyethylene geo-membrane. A few materials that have been tested for use in landfill liner insulation are leachate

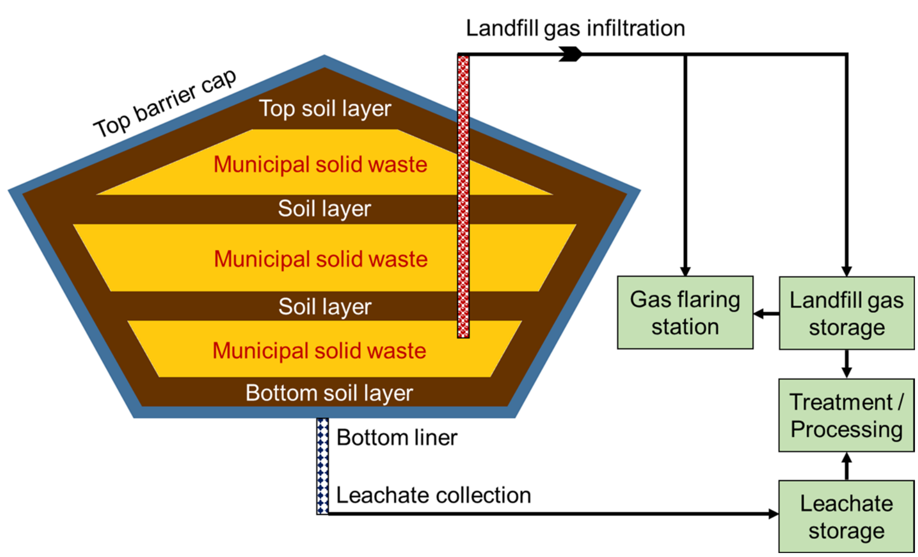

Fig. 6 Typical sanitary landfill. A modern sanitary landfill involves integral components such as landfill foundation, bottom-liner, barrier cap, landfill leachate and gas collection systems, gas flaring station, municipal solid waste and soil layers

collection sand, chipped tires, polyurea foam, polystyrene boards and encapsulated fiberglass (Benson et al. 1996).

A landfill liner can deteriorate with time but during its lifetime as it retards the permeation of leachate into underlying aquifers or adjoining rivers. The durability, efficiency and longevity of landfill liners are determined by the tensile strength, tensile stress cracking as well as resistances to tear, impact and puncture. According to the US Environmental Protection Agency, the landfill liners may delay the permeability of municipal solid waste leachate into groundwater for hundreds of years but will eventually fail due to environmental stress (National Research Council 2007).

A proper leachate collection system at the bottom bed of landfills can also check the leachate discharge into the groundwater and aid in its efficient collection to storage tanks. Driven by the force of gravity, the leachate migrates downward in a landfill reaching the sloping bottom-liner system where it is collected through large perforated pipes by mechanical pumping. The national regulations and standards usually control the design of the leachate collection system. The regulatory laws and standards allow the construction of the collection system that can hold a particular amount of leachate before it is extracted via pumping. In the USA, a maximum permissible leachate buildup above the liner before extraction is 0.3 m (Townsend et al. 2015). The leachate pumped from the landfill is stored in a storage tank or pond before being routed to an appropriate treatment facility either on-site or off-site.

Anaerobic conditions are developed inside a landfill due to several layers of soil on the disposed of organic matter, which results in anaerobic digestion and landfill gas generation. The predominance of methane in the landfill gas makes it valuable for extraction and upgrading as alternative fuels. An engineered landfill is equipped with a landfill gas collection and storage system. The wastes are compacted inside a landfill. Hence, as the landfill gas is generated at high pressures, it tends to escape into the atmosphere through the soil cover. Its combustible nature poses fire hazards, whereas the persistence of toxic gases such as volatile organic carbons, organosulfur compounds, hydrocarbons and CO_2 pose health hazards. Furthermore, the high concentrations of CH_4 and CO_2 in landfill gas could also contribute to the increase in the concentration of these greenhouse gas emissions in the atmosphere if not sequestered. Therefore, extraction points, e.g., commonly used vertical wells located inside a landfill come in contact with the disposed of wastes to collect the gases. The recovered gas is either flared on the landfill site or collected in tanks. The collection of landfill gas is achieved through mechanical pumps and gas extraction systems for further routing to gas treatment and conversion facilities.

Landfills have a particular volume to accommodate the disposed waste after which they are covered with a final layer of soil and a barrier layer in modern landfills. The process is also known as capping, which reduces the penetration of water from rain or snow into the landfill and possibly lowering the incidence of landfill gas generation. Compacted soil and geosynthetic membranes are used as the top barrier cap, whereas highly permeable layers are spread above and below the barrier cap to route water as storm water and facilitate gas removal, respectively, through evapotranspiration (Townsend et al. 2015). Landfill closure should also ensure the prevention of soil erosion from the barrier cap surface through grassing the topsoil cover. The top cover and bottom bed of an engineered landfill facility are extremely critical in determining its environmental impacts. The top cover, i.e., soil, prevents the foul odor, as well as breeding of foraging birds, animals, rodents, pests and infectious microorganisms. In contrast, the bottom bed prevents the discharge of leachate and the emission of landfill gases. The deposition of municipal solid waste should be done for about 0.5 m in a landfill and compacted appropriately (Kumar et al. 2011). Besides, the surface of the freshly deposited solid wastes should be covered with about 0.15 m of soil at the end of each day.

Landfill leachate

Landfill leachate or municipal waste leachate originates from municipal solid waste treatment plants, landfills, anaerobic digesters or composting piles (Tałałaj et al. 2019). It poses serious environmental concerns for remediation due to high organic matter (e.g., carboxylic acids and dissolved solids), toxic chemicals, inorganic salts, heavy metals, ammonia, minerals and xenobiotic organic compounds (Wiszniowski et al. 2006; Pasalari et al. 2018). The refractory or non-biodegradable compounds such as humic substances, e.g., fulvic and humic acids, dominate the organic fraction of landfill leachate (Kumar et al. 2011; Gong et al. 2017). These environmental pollutants are present in high concentrations in the leachate and originate from pharmaceuticals, personal care products, industrial and household chemicals.

Landfill leachate exhibits acute and chronic toxicity and is classified hazardous because it can permeate into groundwater leading to biomagnification (Mishra et al. 2019). The penetration of landfill leachate into the soil is a common worldwide problem in landfills. In the case that the open dump landfills and semi-controlled landfills are situated in low-lying coastal areas, the leachate may seep and contaminate the flowing water. Heavy downpours and thawing of permafrost in polar countries may also lead to the seepage of municipal solid waste leachate into groundwater or mixing with surface water.

This percolation of leachate into the groundwater and soil is more apparent in developing and third-world countries where the landfills lack the baseliners and/or leachate collection systems and treatment facilities. The transportation of landfill leachate through the soil to groundwater is subject to soil geology and aquifer's hydraulic conditions, which also affects the concentration, deposition and permeation of pollutants. The mixing and movement of the pollutants in leachate to the groundwater is mostly through advection, diffusion and dispersion (Han et al. 2014; Samadder et al. 2017). As mentioned earlier, landfill leachate can be prevented from percolating and discharging into the groundwater with the application of a proper leachate collection system at the bottom bed of landfills.

Landfill leachate requires certain treatment before considered safe for disposal into natural water bodies. A few of such leachate remediation pathways include anaerobic biological treatment, e.g., anaerobic bioreactors and anaerobic lagoons; aerobic biological treatment, e.g., activated sludge and aerated lagoons; physicochemical treatment, e.g., air stripping, chemical precipitation, pH, oxidation and reduction; coagulation using alum, lime and ferric chloride; as well as adsorption, e.g., activated carbon adsorption and ion exchange resins (Raghab et al., 2013). The treatment of municipal solid waste leachate largely depends on chemical oxygen demand, biological oxygen demand, ammonium and absorbable organic halides (Ehrig et al. 2011). Chemical oxygen demand measures the amount of oxygen consumed by reactions in a solution. On the other hand, biological oxygen demand measures the amount of oxygen consumed by microorganisms during the aerobic decomposition of organic matter at a particular temperature.

Han et al. (2016) assessed the intensity of groundwater contamination by near the municipal solid waste landfill sites in China and identified around 96 groundwater pollutants, 3 organic matter indicators, 2 visual pollutants and 6 aggregative pollutants, which also included inorganic salts, heavy metals, xenobiotics and pathogenic microorganisms. The initial incidence of groundwater contamination appeared after five years of landfill stage and heightened thereafter, but as the landfill aged for 25 years, the groundwater contamination lowered. Moreover, the groundwater contamination was mostly limited to a perimeter of 1 km from the landfill with the most serious contamination appearing within 200 m. The level of groundwater contamination varied considerably between different landfills in China depending on the composition and/or properties of municipal solid waste being landfilled. Besides, the occurrence of different contaminants in the groundwater was also influenced by seasonal rainfall, regional disparity, landfill age and pollutant migration distance. Han et al. (2014) evaluated the environmental impacts of an uncontrolled landfill in China and determined that the shallow groundwater within 30 m depth near the landfill was not suitable for drinking due to the extremely high concentration of pollutants from the leachate.

It is well accepted that the high levels of pollutants present in the landfill leachate could pose a serious threat to human health as well as terrestrial and aquatic animals near the landfill sites. The toxic heavy metals, metalloids and minerals at a concentration beyond the permissible limits can cause diseases such as Minamata, arsenicosis, blue baby syndrome, pulmonary fibrosis, pneumoconiosis, Wilson disease, hepatic cirrhosis, encephalopathy, argyria, alopecia and even cancer (Medscape 2020). However, direct health hazards are difficult to quantify due to the lack of short-term and long-term exposure studies.

Landfill gases

Landfills also produce landfill gases because of thermal, chemical and biological reactions. Because of the increase in temperature in landfills, the evolution of gases can occur from volatile compounds present in municipal solid waste such as alcohol and naphthalene. Several chemical reactions between different waste species can also take place in the landfill after being mixed during disposal, which can lead to the release of gases. Finally, microbial hydrolysis, decomposition and fermentation can also occur within the landfill. The activity of methanogenic bacteria is relatively higher in the landfill bed, which is devoid of air or oxygen favoring anaerobic decomposition.

Figure 7 illustrates the mechanism of landfill gas formation through a variety of chemical reactions such as hydrolysis, fermentation, anaerobic oxidation, acidogenesis, acetogenesis and methanogenesis. Bacterial communities involved in anaerobic digestion of organic wastes in a landfill and subsequent gas formation are hydrolytic fermentative bacteria, proton-reducing acetogens, hydrogenotrophic methanogens and acetoclastic methanogens (Demirel and Scherer 2008). The initial hydrolysis of organic matter in

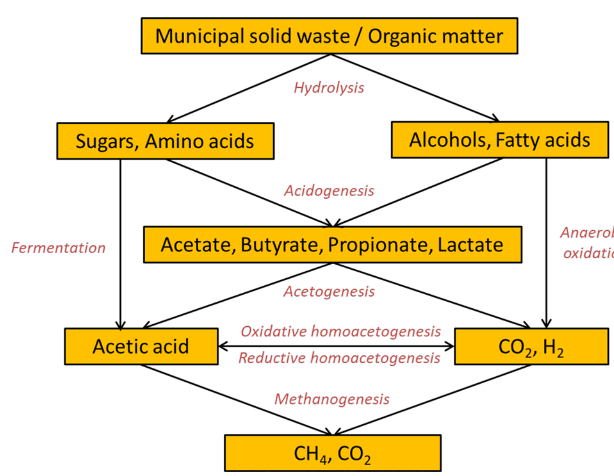

Fig. 7 Mechanism of landfill gas formation in sanitary landfills. The formation of landfill gas involves a variety of chemical reactions such as hydrolysis, fermentation, anaerobic oxidation, acidogenesis, acetogenesis and methanogenesis. Adapted from Demirel and Scherer (2008)

municipal solid waste leads to the generation of sugars, amino acids and fatty acids by fermentative microorganisms and anaerobic oxidizers. These organic monomers are further degraded to acetate, butyrate, propionate and lactate by acidogenic bacteria as the intermediate products. Acid fermentation is enhanced by high moisture content and organic matter during the early stages of a landfill's lifetime, which produces volatile fatty acids such as acetic, butyric, propionic and lactic acids (Kumar et al. 2011). As the landfill matures, acetotrophic and methanogenic phases occur. The acetate-oxidizing bacteria can convert acetate to H_2 and CO_2 through oxidative homoacetogenesis or convert H_2 and CO_2 to acetate through a reverse reaction, i.e., reductive homoacetogenesis (Demirel and Scherer 2008). Finally, through acetogenesis, acetate-oxidizing bacteria convert acetate to CH_4 and CO_2, which are the main components of landfill gas. Besides, the competing species of acetotrophic methanogens also convert the CO_2 and H_2 to CH_4. Acetogenesis and methanogenesis are promoted at high concentrations of H_2 ($\geq$500 Pa), whereas low concentrations of H_2 ($\leq$40 Pa) favor acetate oxidation (Demirel and Scherer 2008).

Landfill gas is a major contributor to global warming because of its two major components such as CH_4 and CO_2. It should be noted that the global warming potential of CH_4 is 25 times more than that of CO_2 and has a lifetime of 12 years in the atmosphere (Nanda et al. 2016d). Landfills are also ranked as the third-largest contributor of CH_4 in the USA after the fossil fuel industry and agriculture, especially livestock farming (USEPA 2020). Moreover, the high concentration of combustible CH_4 in landfill gases also has potential risks of accidental fires and explosions.

Landfill gases are primarily produced by methanogenic bacteria as it contains 55% CH_4 and 45% CO_2 (Ehrig et al. 2011), followed by traces of CO, N_2, volatile organic carbons, benzene, toluene, xylene, carbon tetrachloride, hydrocarbons, and organosulfur compounds (Narayana 2009). The non-methane organic compounds in landfill gases include hazardous air pollutants, volatile organic carbons and odorous compounds, which could also comprise about 39% of total gas emissions from certain landfills (Davoli et al. 2010). The composition of landfill gas depends on the properties and amount of biodegradable solid wastes in the landfill, decomposition phase, available oxygen, moisture content, pH and microbial population (Davoli et al. 2010). However, the composition of landfill gases changes with time and any of the above-mentioned limiting factors. Flaring of landfill gases on-site also produces emissions containing dioxins, furans, polycyclic aromatic hydrocarbons, polychlorinated dibenzodioxins and polychlorinated dibenzofurans, which could have carcinogenic effects upon regular exposure (Davoli et al. 2010).

The formation of landfill gases can occur spontaneously or may take 0.5–3 years after waste disposal but reduces thereafter as the landfill matures. Therefore, it is essential to recover the landfill gases within three years of landfill's active operation. The crude landfill gas after extraction contains a substantial amount of water, which is contaminated with high levels of chlorinated hydrocarbons. The water in the crude landfill gas stream is separated by condensation following the separation of chlorinated hydrocarbons. The wastewater stream is mixed with the leachate only after the contaminant concentration is equivalent to that of the leachate.

Similar to landfill leachate, regular exposure to gas emissions from landfills also pose adverse health impacts to human beings habituating within a certain residence distance from the landfill site. There is a widespread concern relating to the unpleasant odors produced by landfill gases, which is considered more as a nuisance than a health risk. However, nearby residents and landfill operators are believed to be vulnerable to potential adverse health impacts from long-term exposure to landfill gases. Frequent exposure to landfill gases may also lead to abnormalities such as emotional stress, anxiety, uneasiness, depression, headache, nausea, vomiting, asthma, bronchitis, respiratory problems, suffocation, asphyxiation, chronic obstructive pulmonary disease, eye and skin irritation, congenital anomalies, neurological disorders, liver problems and cancer (Narayana 2009; Palmiotto et al. 2014). However, there is limited epidemiological evidence with inadequate consistency in the observations on health implications and mortality caused by landfill gases (Palmiotto et al. 2014).

Bioreactor landfill

A bioreactor landfill is an engineered modern landfill that shifts the paradigm of waste landfilling from storage to treatment. Compared to conventional landfills, bioreactor landfills have several advantages such as (i) enhanced leachate quality, (ii) storage and partial in situ treatment of leachate, (iii) high production rate and yields of landfill gases, (iv) efficient gas recovery for on-site flaring, (v) early waste stabilization, (vi) enhanced decomposition of biodegradable components in municipal solid waste leading to the faster settlement, (vii) cost-efficient and time-efficient post-closure landfill monitoring, (viii) reduced toxicity of wastes due to aerobic and anaerobic digestions, (ix) lower environmental impacts due to less incidence of groundwater pollution and greenhouse gas emissions and (x) increased potential for waste-to-energy conversion (Reinhart et al. 2002; Warith 2002; Kumar et al. 2011). Moreover, bioreactor landfills also appear to be relatively efficient for the removal of hazardous organic contaminants by the following: (i) optimizing conditions for biodegradation, (ii) stripping volatiles by high gas production and (iii) contaminant immobilization via humification (Reinhart et al. 2002). Compared to conventional landfills, bioreactor landfills reveal annual cost savings in the range of $75,000–500,000. Moreover, bioreactor landfills also demonstrate a cost differential of $1.40 to $2.15 per tonne in favor of dry landfills (Gambelin et al. 1998).

Bioreactor landfills can lead to faster mineralization and stabilization of municipal solid waste by accelerating anaerobic degradation of biodegradable components. The characteristic changes in the quantity and quality of leachate and gas emissions determine the intensity and duration of waste stabilization in a bioreactor landfill. A bioreactor landfill implements the recirculation of leachate to enhance the microbial activity for faster degradation and transformation of organic wastes, which is different from a traditional landfilling technology (Fig. 8). Another feature that differentiates bioreactor landfills with conventional landfills is the addition of hydrolytic, fermentative, putrefying and methanogenic microorganisms to create a conducive environment in the landfill for waste decomposition. Bioreactor landfills are equipped to recirculate leachate in different configurations, regulate temperatures, supplement microbial growth nutrients including pH buffer and recover landfill gases for partial storage and on-site flaring.

The main reason for leachate recirculation in bioreactor landfills is to increase the moisture content for microbial growth. The uniform distribution of leachate inside a bioreactor landfill stabilizes the wastes in each layer through hydrolysis, acid formation, methanation and final maturation phases. As mentioned earlier, leachate recirculation in the bioreactor landfill facilitates the conversion of biodegradable ingredients of municipal solid waste into intermediary degradation products and gases, e.g., CH_4 and CO_2 via enhanced hydrolysis, fermentation, acidogenesis, acetogenesis, anaerobic oxidation and methanogenesis (Fig. 7).

The typical temperature inside a bioreactor landfill ranges from 45 °C to 60 °C, although methanogenic bacteria prefer temperatures between 35 °C and 45 °C for their optimal activity (Kumar et al. 2011). Methanogenesis is highly essential for stabilizing municipal solid waste. Since methanogenic bacteria necessitate anaerobic conditions, an optimum redox potential below − 100 mV can also be attained in a bioreactor landfill. The methanogenic bacterial population is also proliferated under alkaline environments in a bioreactor landfill with pH levels between 6 and 8 and alkalinity around 2000 mg/L (Kumar et al. 2011).

Bioreactor landfills can be classified into anaerobic, aerobic and semi-aerobic landfills (Fig. 9). The fundamental differences between these bioreactor designs are related to their operations, configurations and alignments for leachate recirculation, landfill gas infiltration and optional air injection systems. The principle of the anaerobic bioreactor is to provide an anaerobic environment for the activity of facultative and anaerobic microorganisms, especially acidogenic, acetogenic and methanogenic bacteria. Anaerobic bacteria convert biodegradable wastes in the bioreactor landfills to volatile fatty acids and eventually to landfill gases, e.g., CH_4 and CO_2. The steps involved in the anaerobic degradation of organic wastes to leachate and landfill gases occurs through several sequential pathways such as hydrolysis, acidogenesis, acetogenesis, methanogenesis, anaerobic oxidation and fermentation as described earlier (Fig. 7).

Carbon, nitrogen and phosphorus present inherently in the disposed of wastes inside the landfill can significantly affect

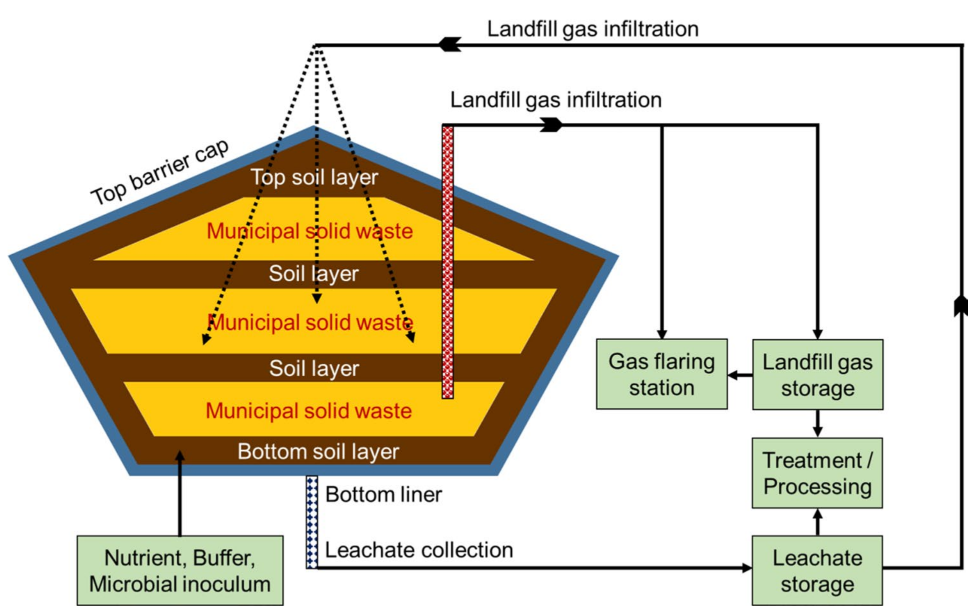

Fig. 8 Typical bioreactor landfill. Bioreactor landfills are different than conventional landfills with the occurrence of hydrolytic, fermentative, putrefying and methanogenic microorganisms to create a favorable environment in the landfill for the decomposition of solid waste

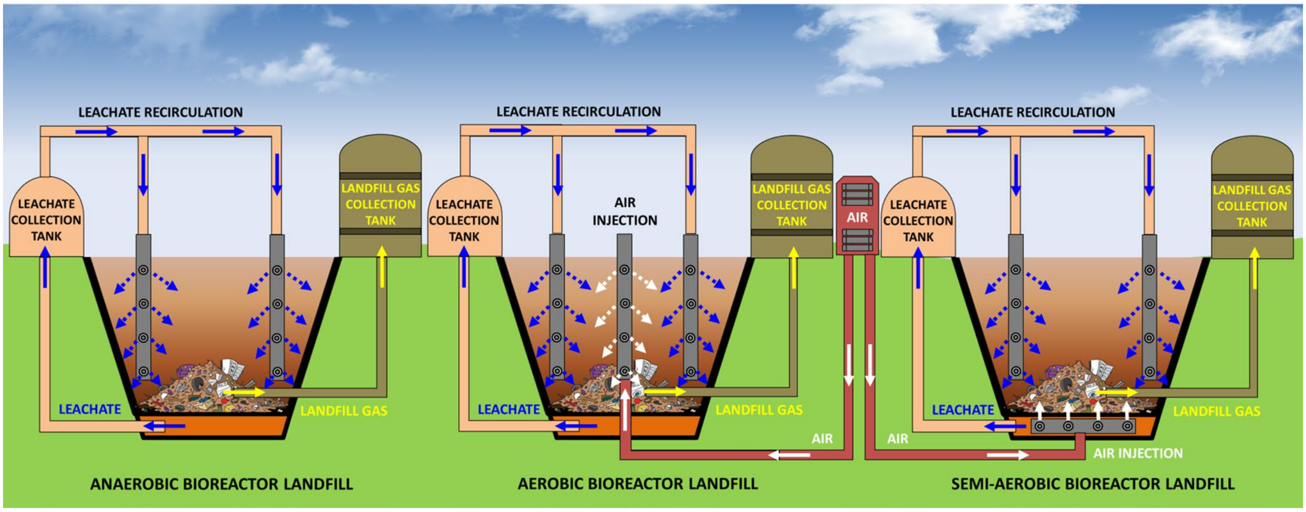

Fig. 9 Anaerobic, aerobic and semi-aerobic bioreactor landfills. Anaerobic bioreactors create an anaerobic environment for facultative and anaerobic microorganisms including acidogenic, acetogenic and methanogenic bacteria. The landfill gas and leachate collection systems are also integrated with anaerobic bioreactors

the microbial growth phases during the anaerobic biodegradation. Leachate is usually recirculated through perforated wells or other delivery systems to optimize the moisture content of the bioreactor landfills. Moisture content optimal to maintain anaerobic degradation in an anaerobic bioreactor landfill is about 35–40% field capacity in contrast to the typical landfills moisture content of 10–20% field capacity (Warith 2003). Anaerobic biodegradation is a relatively slower process, which may gradually release the leachate and gases for many decades even after landfill closure (Ritzkowski et al. 2006). The advantages of anaerobic bioreactor landfills are less waste stabilization times and high concentration of CH_4 in the landfill gas that can be used for flaring (Omar and Rohani 2015). However, the landfill gases also have high H_2S content, which requires stripping with additional expenditure. Moreover, the leachate generated from bioreactor landfills also has high concentrations of ammonia and volatile fatty acids, which require secondary treatments with added costs.

Aerobic bioreactor landfills accelerate waste degradation by creating oxygen-surplus conditions for aerobic microorganisms. In such landfills, aerobic microorganisms gain energy by oxidation of organic molecules to produce primarily CO_2 and water. Aerobic degradation is faster than anaerobic degradation because aerobic microorganisms multiply at a faster rate due to aerobic respiration, which is more efficient in generating energy than anaerobic respiration. In aerobic bioreactor landfills, aeration is promoted through the injection of air into the waste mass and soil layers. The injection of air into landfills retards the growth of anaerobic microorganisms and lowers methanogenesis and CH_4 formation from an initial 60–10% within 7–10 days (Omar and Rohani 2015). Air injection methods could be through active aeration with off-gas extraction, active aeration without off-gas extraction, passive aeration, intermittent high-pressure aeration and intermittent low-pressure aeration (Ritzkowski and Stegmann 2012). The rate of aerobic biodegradation depends on the oxygen concentration, rate of aeration, mesophilic temperatures, e.g., 15–40 °C, moisture content, e.g., 50–60% field capacity and pH 6.5–8 (Omar and Rohani 2015).

The main advantages of aerobic bioreactor landfills are shorter waste stabilization times, faster biodegradation and removal of moisture by air stripping. The leachate from aerobic bioreactor landfills also has reduced chemical oxygen demand, biological oxygen demand and total organic carbon and negligible ammonia generation. However, the gas generated from such landfills because of aerobic degradation contains mostly CO_2 and only traces of CH_4, which is not suitable for flaring. Owing to less methane and ammonia generation, gas and leachate are relatively less odorous, which is a big social advantage. Nonetheless, uniform and sufficient aeration in such landfills adds to the overall process economics.

The alignment of perforated injection wells for air and leachate differentiates the aerobic and semi-aerobic bioreactor landfills. Semi-aerobic bioreactor landfills provide partially oxygen-deficient conditions to boost both aerobic and anaerobic microorganisms. This suggests that methanation, hydrolysis and fermentation operate in parallel, although depending on the concentration of oxygen, the aerobic and anaerobic reactions could compete and the respective aerobic and anaerobic microorganisms localize in their optimal niches within the landfill. In aerobic bioreactor landfills, the air is injected into the aerial space of the landfill, whereas in semi-aerobic bioreactor landfills, the air is passed through the waste layer from the bottom of the landfill. In some configurations, air can also flow naturally through the leachate collecting pipes (Yang et al. 2011). In such configurations, the additional cost of air injection is lowered. In addition to being economical, other advantages of semi-anaerobic bioreactor landfills are lower waste stabilization times and less methane yields (Huang et al. 2008). However, the presence of methane in landfill gas and the addition of air can be potentially hazardous for flammability and explosions at high pressures.

Reinhart et al. (2002) have summarized a few limitations of bioreactor landfills. One of the major disadvantages is ballooning and tearing of plastic surface liners due to the sealed system required for creating an anaerobic environment. This problem can also be overcome by the continuous collection of the produced gases. In the large-scale bioreactor landfills, where the provision of uniformly distributed leachate infiltration is not possible, the use of more permeable intermediate cover could help reach field capacity. However, the use of low-permeable intermediate cover can cause seepage of the leachate due to a lack of infiltration through the compacted heterogeneous waste. For instance, the leachate seepage due to non-uniform leachate recirculation reached up to 85 m away from the recirculation wells in the Keele Valley landfill in Toronto, Canada (Reinhart et al. 2002). Furthermore, leachate recirculation can lead to short-circuiting hampering the capacity required for a landfill operation. Short-circuiting could also be caused by increased condensate production in the landfill gas collection pipes. Plugging of the leachate collection/infiltration piping as well as gas collection systems is another technical issue. During dry seasons, the leachate produced by the bioreactor landfill might not be sufficient to moisturize the wastes, thereby requiring additional water sources. Channeling leads to instantaneous leachate production, but a continuous leachate recirculation could increase the uniform wetting of the waste and decline the real leachate generation because the moisture content in the waste would approach field capacity.

Warith (2002) performed experimental and field trials on the biodegradation of municipal solid waste in a bioreactor landfill site located in Nepean, Ontario, Canada, that recirculated leachate through infiltration lagoons for eight years. It was noted that the pH of the leachate transitioned from acidic to alkaline, i.e., pH 7–8, after two years of recirculation, reducing the organic load, biological oxygen demand and chemical oxygen demand. The biodegradation of municipal solid waste occurred at a higher rate in the bioreactor landfill, which not only reduced the contaminant life span but also the cost for long-term environmental monitoring. Nevertheless, there are limited studies on operational full-scale bioreactor landfills. Bioreactor landfills constitute a very small fraction, i.e., 5–10% of all landfills worldwide, although there is a growing interest in experimenting leachate recirculation in some active sanitary landfills (Reinhart et al. 2002). Some bioreactor landfills located in the USA, particularly in Delaware, Georgia and Maryland, have also demonstrated high levels of waste degradation within the short life span of the landfill (Reinhart et al. 2002).

The fate of remaining waste constituents in the bioreactor landfill over a long-term period is largely unknown, although it is believed that they would undergo continual biological and chemical degradation. The perception that bioreactor landfill technology is relatively new with lack of demonstrative evidence, unclear cost implications and regulatory constraints causes reluctance for its commercial applications. Additionally, less information is accessible on landfill microbiology, which could provide many insights on the synergistic and antagonistic functionalities within a heterogeneous ecosystem, i.e., landfill. Therefore, more research relating to sustainability, lifecycle assessment, techno-economic analysis, leachate hydrodynamics, the addition of air and possible technical challenges is required.

Landfill mining and reclamation

The historic purpose of landfilling is to store the assorted wastes at the lowest cost for indeterminate periods. However, the socio-environmental concerns such as global warming by greenhouse gas emissions including methane, groundwater pollution by highly toxic liquid leachates and heavy metals, as well as malodorous grievances in the landfills' vicinity that limit urban development and social acceptance are some long-term implications of active and closed landfills. As a strategy to address such problems, landfill mining and reclamation have emerged in concept to excavate, process, treat and recycle previously buried waste materials. Following the excavation of closed landfills, the screening of the dumped waste can separate metals, partially degenerated plastics, inert materials, e.g., concrete, stone and gravels, as well as decomposed organic materials, e.g., humic substances in soil. While the humic materials can be applied as organic fertilizer, metals can be recycled and plastic wastes having high calorific value can be treated through waste-to-energy technologies, e.g., pyrolysis, liquefaction and gasification for energy and material recovery (Zhou et al. 2015).

The concept of landfill mining was first executed in 1953 to excavate the Hiriya Landfill in the City of Tel Aviv, Israel, for recovering the decomposed wastes as fertilizers for agricultural applications, particularly in orchards (van der Zee et al. 2004). Once a toxic notorious landfill in Israel spanning half-mile long, 87 yards above sea level and storing 25 million tonnes of wastes, following mining the Hiriya Landfill has been reclaimed into Ariel Sharon

Park (Mordas-Schenkein 2015). Despite being a treasured tourist attraction, the Ariel Sharon Park, formerly Hiriya Landfill, also houses three recycling plants and waste-to-energy facilities to sort and converts 3000 tonnes of household wastes, 1500 tonnes of construction debris and 250 tonnes of green landscape wastes daily into fuel, electricity, compost and fertilizers. This is a success story of how a tarnished landfill can be transformed into a lively common still being functional.

Soon after the initial implementation of landfill mining in Israel in 1953, there was a growing interest in the perception of using mining to remediate hazardous landfills with the potential to extract the minerals and other deposited natural resources. During the 1990s, the stringent federal regulations in the USA relating to landfill management were implemented, which made it harder to obtain permission for new landfills, shifting the attention to reutilize the closed landfills through mining (Johansson 2016). The environmental regulations were related to requirements for landfill liners, proper leachate collection systems, groundwater monitoring and landfill soil remediation (Wagner and Raymond 2015). The motivation for landfill mining during this period intensified due to lack of space for new landfills, pollution liabilities, environmental and waste treatment costs by new government regulations along with the benefits of landfill cover material and waste-to-energy conversion (van der Zee et al. 2004).

A few older landfills in the USA and abroad were established much before the landfill liner technology was discovered, which often discharge their hazardous leachate into underlying aquifers polluting the groundwater. As a legal pollution liability, the US Environmental Protection Agency required the closed landfills to be monitored periodically to prevent environmental hazards requiring substantial expenditures. Mining the closed landfills to install bottom and intermittent liners was found to be a cost-effective resort with complementary benefits of material and energy recovery. In Asia and Europe, the drivers for mining a closed landfill is chiefly for its reclamation due to lack of space for new landfills and urban development (Johansson 2016).

In recent years, landfill mining has gained interest among landfill owners due to the increased commodity prices and revenue generation potentials through the recycling of excavated wastes and energy production. In a case study, the market for mining nearly 3800 closed landfills in the Netherlands was estimated to have a domestic profit potential of approximately €150–200 million (van der Zee et al. 2004). Some case studies have estimated the landfill mining costs in a few developed countries such as in the Netherlands, i.e., \$100–130/Mt of municipal solid waste, the USA, i.e., \$40–120/Mt of municipal solid waste and Europe, i.e., \$75/Mt of municipal solid waste (Wagner and Raymond 2015). However, the techno-economic analysis, energy feasibility and environmental risk assessment remain unclear and conceptual due to the deficiency of large-scale field studies on landfill mining (Krook et al. 2012).

Landfill mining not only reduces the landfill footprint by clearing dumpsite space but also recovers valuable recyclable materials, compost and combustible landfill gases (Johansson et al. 2017). A key feature of landfill mining is to reduce the volume of total landfill mass encapsulated within the closed landfill, especially for creating space for new waste disposal by excavating partially/fully decomposed organic materials and potentially recyclable products. Mining of modern sanitary landfills and bioreactor landfills that have their wastes stabilized can be relatively feasible and cost-effective because the biodegradable wastes are more easily screened with accessibility to non-biodegradable materials. However, the quality of non-biodegradable detritus, e.g., plastics, scrap tires, rubber and glass for recycling and reprocessing, is usually not high due to the presence of soil, silt, clay and other earth particles. Regardless, metallic components such as aluminum, steel, tin, iron and copper could still be valuable after excavation.

Landfill mining can be broadly classified into in situ mining and ex situ mining (Jones et al. 2013). The in situ landfill mining involves the resource recovery activities (e.g., recovery of landfill gases and leachate as well as the removal of contaminants from soil and water) on the landfill site without excavation of the stored waste stream. Conversely, ex situ landfill mining refers to the recovery of resources through the excavation of the stored waste streams for further treatment off-site. The preference of in situ and ex situ mining is dependent on intrinsic parameters, e.g., landfill size, location, age, type and waste composition as well as extrinsic parameters, e.g., feasibility of suitable recycling and waste-to-energy technologies and socio-economic boundaries (Jones et al. 2013). A few other factors of consideration before identifying the relevance of landfill mining are the following: (i) composition of the originally dumped wastes, (ii) historic operating and treatment procedures, (iii) extent of waste degradation, (iv) facilities for landfill gas and leachate collection and (v) available markets for recycling the recovered materials (Environmental Alternatives 2020). Other environmental and economic benefits of landfill mining are: (i) cost reduction for landfill closure and post-closure, (ii) re-utilization of recovered soil fraction as landfill cover material and (iii) reclamation of landfill space for reuse.

Mining and excavation of landfills also have secondary benefits such as aeration, which could enhance the activity of aerobic microorganisms and retard the methanogenic bacterial population, thus lowering the methane generation in the landfill gases. Landfill mining may also be indispensable for abiding by environmental regulations by removing hazardous materials and ensuring proper protective measures before the entire landfill mass is replaced. However, the safety of mining personnel should be of prime importance because the excavation of some dumpsites may lead to the release of highly obnoxious landfill gases, which could only have health hazards but also fire risks. Some methanogenic bacteria are localized in some intrinsic sites inside the landfill that are devoid of oxygen leading to greater decomposition rates. Due to compaction of the wastes and intermittent soil layers, such microbial active zones inside a landfill may result in the high-pressure buildup from methane-rich landfill gases. Excavation of such areas inside the landfills can lead to gas leakage, landslides and collapse due to the sudden release of the gas pockets making the mining operators vulnerable. On the other hand, for the older landfills that are deprived of proper leachate collection systems, mining may induce the discharge of the accumulated leachate onto the surface or into the groundwater.

Opportunities, threats and best practices in the management of municipal solid waste

(i) Decentralization of municipal solid waste management

A decentralized approach for the management of municipal solid waste can be achieved with active citizen participation and awareness programs. Under such a decentralized system, a citizen is more informed about the 4Rs principle, i.e., reduce, reuse, recycle and recover. The residents become less dependent on the municipality's waste collection/segregation system, which improves the primary waste collection at the source. Strong cooperation and consensus between the government and community is essential in planning and implementing a decentralized management system for municipal solid waste (Srivastava et al. 2005). Under a decentralized system, low-cost manual composting can also be integrated to provide employment opportunities and generate revenues by selling the compost (Narayana 2009).

(ii) Segregation of municipal solid waste at the source

The non-biodegradable materials, e.g., plastics and glass, in municipal solid waste stream create impediments in its treatment processes. It also increases the labor and operating costs related to their segregation and sorting at the solid waste treatment site before landfilling and recycling or waste-to-energy technologies. These materials have secondary market values and are best suited for alternate recycling processes such as pyrolysis, liquefaction or gasification. Without segregation of municipal solid waste into different streams, i.e., organic, plastic, metals, glass, inert materials, textiles and paper, even the best waste management systems are rendered impractical. Owing to the heterogeneous nature of municipal solid waste streams, households, institutions and industries should take the first responsibility for waste segregation at the source. This could dramatically curb the costs for downstream processing of solid wastes. The segregation of wastes at the source could also improve the efficiency and sanitation of municipal solid waste collection. This practice also supports the decentralized management system for municipal solid waste. The diversion of organics and recyclables into the garbage at the household level should be prevented wherever practical. Innovation in waste segregation solutions and enforcement of disposal restrictions at the source could influence this approach.

The residents should be conscious of the concept of waste classification, i.e., recyclable, non-recyclable, flammable, nonflammable, inert, glass, composites, plastics, paper, food waste, electronic wastes, pharmaceutical wastes as well as construction, demolition and renovation wastes. However, the large municipal solid waste collection trucks and their built-in collection methods are not always conversant with this innovation. This would also require the municipality or waste management agency to provide the residents with separate garbage collection bags/containers with distinguished colors, legible texts and pictograms of accommodating wastes. In Canada and the USA, the level of waste management service varies by municipality. For example, large urban communities are often provided with curbside garbage collection service, while the small rural communities are offered with drop-off collection service.

The municipal solid waste recycling industries should also improve their downstream processing technologies, product standards, customer relationship management, as well as expand alternate markets for end-products and by-products. For instance, most of the solid waste management firms in the developed countries provide management and environmental solutions for residential solid waste, as well as commercial and industrial wastes. Such organizations run collection operations, transfer stations, organic processing facilities, waste-to-energy facilities and landfills. They serve as a good example of a modern municipal solid waste management facility in providing the customers with up-to-date information on garbage collection schedules, garbage drop-off locations, garbage pickup and container delivery. To keep pace with technology, such organizations also offer updated Web sites and mobile apps through which the customers can make their transactions relating to garbage pickup and drop-off. Furthermore, Japan has proved as a country keen on reducing wastes and increasing recycling. The residents are responsible for sorting their wastes at the source into segregated sections such as flammable, nonflammable, plastic, polyethylene terephthalate bottles, cans, paper, Styrofoam, cardboard boxes, glass, metals, batteries and electronic wastes. With a stringent garbage policy, Japan incinerates 80% of its garbage and most of the rigorously sorted wastes are recycled (Onishi 2005).

(iii) Hygienic and safe handling of municipal solid waste

Municipal solid waste contains diverse microbial communities, both opportunistic and pathogenic. *Enterobacter*, *Escherichia coli*, *Klebsiella*, *Salmonella*, *Shigella*, *Streptococci* and *Yersinia* are some of the fecal bacteria that usually appear in municipal solid waste (Hassen et al. 2001). These are highly infectious to solid waste handlers and farmers using solid waste-derived composts. The problems of fly and mosquito breeding, odor generation, as well as pests and rodents are also common in open dump landfills and composting areas in developing countries. Additionally, organic pollutants, flammables, volatiles, needles, shards and sharp objects can cause physical injury to handling municipal solid waste and compost. In most developed countries, the workers in all employment sectors including municipal solid waste management are required to complete workplace-specific training tasks relating to occupational health and safety and health hazard awareness. Although such safety training exists in developing countries, it is non-stringently implemented, which leads to a lack of proper awareness and preparedness for health hazards from unhygienic municipal solid waste handling by the operators.

(iv) Flammable landfill gases

Landfill gases are collected unevenly in pockets that can gradually seep out through the soil cover, liner or accumulated wastes. Moreover, compaction and leveling of solid waste at the landfill site and soil covering are rarely observed practices in developing countries (Sharholy et al. 2008). The gas emissions from landfills and anaerobic digesters have potential risks to the operators due to high concentrations of CH_4, CO_2 and CO. These gases may lead to asphyxiation, suffocation, asthma and other respiratory and pulmonary disorders in solid waste operators or people residing close to municipal solid waste disposal sites. Besides, landfill gases can also build up pressure making them highly flammable with uncontrolled accidental fires or explosions.

The disposal sites for municipal solid waste should have well-equipped landfill gas and leachate collection systems as well as emergency preparedness procedures to prevent any vulnerability. Incineration of municipal solid waste also leads to air emissions as well as particulate matter and fly ash that contains heavy metals, dioxins, furans, volatile organic carbons and other harmful contaminants. Entrapment and recovery of particulates and fly ash can prevent their transmission to the atmosphere and persistence in soil, air and water. Moreover, proper preventive measures should be implemented to avoid such health hazards to the municipal solid waste handlers. The environmental monitoring should also be done through visual inspections and routine and seasonal chemical analysis of the landfill soil, leachate and gases for the immediate safety of the landfill operators.

(v) Soil salinity from compost application

Municipal solid waste compost can be applied to agricultural farmlands to enhance the organic matter, fertility as well as demand for carbon, nitrogen and other microelements. Heavy metals comprise a significant portion of assorted municipal solid waste and are also inherited in the compost. Furthermore, the application of compost can significantly increase the metal concentration in the soil portraying adverse conditions for plant growth. The heavy metals and other recalcitrant organic components from the compost can pollute the groundwater by permeation through the soil profile.

Municipal solid waste-derived compost can also be characterized by high salt concentrations, which can cause salinization upon application to soil (Hargreaves et al. 2008). Soil salinity can negatively affect the soil properties such as texture, fertility, pH, electrical conductivity, cation-exchange capacity and water holding capacity, as well as plant growth and productivity (Nanda and Abraham 2013). It is also reported that municipal solid waste-derived compost increases sodium and chlorine levels in the crops, which is concerning to people on low-sodium dietary restrictions (Hargreaves et al. 2008). In addition to agronomic practices such as irrigation, tillage and application of plant growth-promoting rhizobacteria can reduce salinity and osmotic stress by regulating the production of essential phytohormones and antioxidants in plants (Kang et al. 2014). Preprocessing of municipal solid waste and product refinement techniques can help to reduce the concentration of heavy metals from the compost. This could also enhance the organic matter content and agricultural value of the screened compost.

(vi) Sustainable landfill management

Transiting the open dumpsites common in the developing and third-world countries to sanitary landfills is a direct approach toward sustainable landfill management. Moreover, the reclamation and rehabilitation of closed landfills and dumpsites through phytoremediation could also help prevent erosion of topsoil cover from landfills and adsorption of heavy metals and by the plants. Energy crops such as hybrid poplar, oilseed and grass species can be used for phytoremediation and reclamation of contaminated soils near the landfill areas. The plantation of energy crops in closed landfills is highly preferable due to some of their characteristic features such as (i) low cost, (ii) fast growth, (iii) short-rotation harvesting with high biomass yield, (iv) non-seasonal availability, (v) growth in marginal and degraded soils, (vi) resistance to extreme weather conditions, (vii) less-intensive agricultural practices and (viii) no competition with food crops for nutrients and sunlight due to non-edible nature (Nanda et al. 2016b; Singh et al. 2020a, b).

The application of biochar to landfill sites, especially the topsoil cover, is considered as a promising measure for landfill soil remediation, contaminant immobilization and carbon sequestration (Kumar et al. 2011; Gunarathne et al., 2019; Gopinath et al. 2020). Biochar is a solid product obtained from pyrolysis, gasification, torrefaction and carbonization of biomass and other wastes such as municipal solid waste, sewage sludge and industrial effluents (Azargohar et al. 2019). Biochar is highly mesoporous and rich in carbon, which acts as an adsorbent material for immobilization of pollutants and nutrients, as well as a niche for essential plant growth-promoting microorganisms in the soil (Nanda et al. 2016a). It helps in promoting plant growth, soil fertility and bioavailability of soil nutrients and moisture. Amendment of biochar to landfill sites can significantly enhance slope engineering, particularly soil weight, internal friction angle and cohesion (Kumar et al. 2011). Furthermore, biochar is a low-cost and eco-friendly adsorbent material beneficial in removing both organic pollutants (e.g., dyes, pesticides, phenols, polycyclic aromatic hydrocarbons and solvents) and inorganic pollutants (e.g., metal ions and anions) (Mohan et al. 2014).

(vii) Alternative markets for energy products from the processing of municipal solid waste

Waste-to-energy technologies such as pyrolysis, liquefaction, gasification and anaerobic composting generate specific fuel products such as bio-oil, producer gas, syngas, methane and biochar. It is considered profitable to maximize bio-oil production and minimize biochar yield from pyrolysis and liquefaction. Similarly, in gasification and anaerobic digestion, syngas and methane are more, respectively, profitable than biochar and biosludge. The average estimated costs of bio-oil and biochar are US $740/toe and the US $500/ton, respectively (Nanda et al. 2016a). Bio-oil can be catalytically upgraded to synthetic transportation fuels, whereas biochar finds application as solid fuel, adsorbent, specialty material manufacturing and soil applications. Bio-oils and municipal solid waste leachate can also be used to recover value-added chemicals.

At the commercial level, about 96% of hydrogen is synthesized through steam reforming of natural gas or methane due to its low production cost of US $1.5–3.7 (Balat and Kırtay 2010; Nanda et al. 2017). Hydrogen is a promising energy carrier and energy vector that can be produced from the reforming of methane to replace fossil fuels (Shah et al. 2017; Singh et al. 2018). A new market for highly concentrated methane obtained from landfills and anaerobic digestion of municipal solid waste can be recognized potentially in the steam reforming process to produce hydrogen fuel. Considering the high energy content, the landfill gases can also be utilized for combustion in flare systems or electricity generation using motors or turbines. Landfill gases typically have an energy content of 4–5 kWh/m^3 and a potential to generate about 0.5–2 MW of electricity for an average sized landfill (Ehrig et al. 2011).

(viii) Implementation of "*pay as you throw*" system

"Pay as you throw" is a trash metering and usage-pricing model for disposing municipal solid waste at household, commercial or industrial scales. The "pay as you throw" model is based on the two guiding principles of environmental policy, especially the "polluter pays principle" and the "shared responsibility concept" (Batllevell and Hanf 2008). Under such a model, a price is levied on the residents based on the number of wastes they generate for collection by the municipality or local authority. The charges, restrictions and rules vary as per the municipality. The collected wastes are measured by weight, size, garbage bags, designated tags, garbage containers or other advanced techniques such as radio-frequency identification. Hughes Identification Devices or HID Global, located in Austin, USA, is a manufacturer of secure identification systems including radio-frequency identification tags for waste management (HID Global 2020). The garbage collection truck reads the radio-frequency identification tag installed on the customer's garbage bin during pickup. The truck weighs the garbage bin using the radio-frequency identification detection before emptying following which the customer is billed accordingly.

The “pay as you throw” system can be implemented in three ways, particularly partial-unit pricing, full-unit pricing and variable-rate pricing (Kelleher et al. 2005). Under the partial-unit pricing system, waste management is funded through a flat utility fee, household unit pricing charges or a combination of taxes. The municipality or local authority decides the maximum number of allowable bags for a household. However, extra garbage bags or containers are subject to additional costs. Under the full-unit pricing system, the waste management is financed by the garbage collection fees paid by the resident in advance through purchasing garbage bags, tags, as well as specific size and number of containers or bins.

Waste reduction and diversion are favored under the full-unit pricing system. Conversely, a variable-rate pricing system enables residents to rent specific size and number of the bin from the municipality for their weekly garbage collection. However, the residents are encouraged to rent the smallest bin to reduce their waste generation and save the “pay as you throw” costs (Gray 2018). The volume of garbage, recyclables and yard wastes in excess is also charged separately in most Canadian cities. A weight or volume-based “pay as you throw” system could raise the administrative costs for the municipality or waste management agency while becoming an economic incentive for the homeowners. However, it may cause the illegal dumping of garbage, which is prohibited by law in many countries.

Conclusion

For effective management of municipal solid waste and determining the optimal material recycling, energy recovery or landfilling options, it is essential to identify the characteristics, compositions and heterogeneity of the generated waste. Landfills have been one of the most preferred methods for the disposal of municipal solid waste. Besides, the lack of space for new landfills in highly metropolitan cities is leading to the implementation of waste-to-energy options for the recycling of solid wastes. Diverting municipal solid waste for energy generation is much more superior to landfilling due to lesser environmental impacts such as low greenhouse gas emissions, high-energy recovery potentials and reduced pollution. Although serving as a long-term geological storehouse of wastes, landfills also pose environmental concerns in terms of air pollution, groundwater contamination, global warming and health impacts. Therefore, regulatory protocols such as the installation of landfill liners, soil covers, leachate collection systems, gas recovery and flaring facilities as well as remediation of closed landfills are vital.

Landfills, anaerobic digesters and composting plants generate leachates, which are rich in organics, inorganic metals and harmful contaminants that can pollute the groundwater and aquifers. Landfills also produce landfill gases and volatile components, which pose health hazards to the landfill operators. However, due to a lack of long-term exposure studies and consistent medical data, these health disorders relating to landfill gases are not directly conclusive to landfills. The hydrolysis, decomposition and fermentation of highly degradable organic matter, e.g., food waste, paper and yard waste disposed of in landfills, produce landfill gases. Furthermore, the amount of biodegradable matter, moisture content, pH, temperature, as well as hydrogeological conditions of the landfill including its height and type along with local weather conditions largely determine the production and composition of landfill gases and leachate. Landfill gas is often combustible for its high methane concentration, but its energy recovery has not been widely exploited to its full potential. Bioreactor landfills are modern engineered sanitary landfills that have the potential to enhance the waste stabilization at a relatively faster rate due to the recirculation of leachate and gas infiltration. Depending on the geometry of leachate recirculation and air supply, bioreactor landfills can be classified into aerobic, anaerobic and semi-aerobic types.

Owing to its developmental stages, only tentative conclusions can be made regarding the potential and prospects of landfill mining and reclamation. Landfill mining is a process to potentially generating revenue from the closed landfill through the excavation of dumped wastes, recovery of non-biodegradable materials, i.e., metals, plastics and glass, for recycling or energy generation and decomposed materials, i.e., humic substances for agricultural applications. Landfill mining can be effective in reducing landfill volume for reuse or as reclaimed land for urban development. It is highly relevant to consider the integration of landfill mining into new landfill designs so that the stabilized waste after a certain timescale can be readily accessible for mining, resource recovery and reclamation.

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