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# Sustainable and long-term management of municipal solid waste: A review

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ABSTRACT

This study investigates landfill and incineration waste management strategies as potential and prevalent traditional methods of disposing of municipality-generated waste because of their cheapness and simplicity but requires a high level of management to mitigate their negative impacts. Interestingly, sustainability in municipal solid waste (MSW) is no longer limited to cleaning, uninterrupted operation, and sanitation but entails a bigger picture of a global view of ensuring environmental protection, social balance, economic stability, and a sustainable environment. The review further examined pollutant partitioning for a better understanding of the movement of hydrophobic colloids with different phases such as marine, groundwater, and soil as a factor to be considered when selecting a sustainable MSW management option. Furthermore, the incorporation of cleaner production in any waste management method has contributed immensely to the enhancement of environmental sustainability and cleaner bioresources by tackling the emergence of any environmental depletion that is likely to arise.

## 1. Introduction

The global industrial revolution, urbanization, and increasing human population have been responsible for the persistent rise in the amount of waste generated and other challenges such as energy shortage, mineral exhaustion, etc. (Al-Ghouti et al., 2021). The sources of waste could be domestic, manufacturing activities, industrial processes, and municipal solid waste (MSW) (Khan et al., 2022). Generally, waste is seen as causative for the introduction of contaminants to the environment in the form of organic and inorganic pollutants. Organic pollutants such as food wastes can be considered as bioresources or as a source of biomass, which can be used as either heat, compost, electricity, or bio-fuel (Moya et al., 2017). Polyaromatic hydrocarbons (PAHs), metalloids, polychlorinated biphenyls (PCBs), and mineral soils constitute a major threat among these organic and non-organic contaminants (Khan et al., 2021). The problem of water pollution has been worrisome because of different waste pollutants, which have added to the problem of water shortage globally (Alabsi et al., 2021). It has been established that water shortages for agricultural purposes and drinking are hitting hard, particularly in the arid and semi-arid regions as well as a large number of some southeastern countries of Asia continent as well as Latin America (Alabsi et al., 2021; Bello et al., 2021). Waste generation inefficient management systems present one of the major environmental challenges to urban societies and are therefore recognized as one of the sources of these pollutants (Guerrero et al., 2013). Municipal solid waste management involves many stages viz. the gathering, sorting, storage, transport, processing, and eventual disposal of generated refuse from municipal sources following guiding technical principles, emphasizing the environment, health, and economy to mention but a few (Hazra and Goel, 2009). Several other factors could influence solid waste management, including sources, enabling policies, and social, cultural, and political factors among others. To ensure a sustainable environment, both technical and non-technical factors need to be addressed critically. For the purpose of consistency, our reference point as a generic name for waste through this study shall be a municipal solid waste. Among the existing ways for the management and treatment of MSW, they can only be considered as sustainable if the generated waste cannot accumulate as well as can be fully recovered, reused, and recycled.

## 2. Waste properties and classification

There are various classifications of municipal solid waste; however, hierarchical source classification is suggested. The source classification of municipal solid waste fell into three divisions viz. city/urban, industrial, and rural sources. From these 3 divisions, 7 classes were derived as presented in Fig. 1. The city/urban division mostly contains

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solid waste that originates from where human domiciles, that is not in any way influence the number of people domiciling such as settlements (Buenrostro et al., 2001). Moreover, this division is subdivided into residential and non-residential sources, while the rural division includes all the waste from agricultural and animal husbandry activities. Moreover, the industrial sources include all the facilities regardless of their size. As specified earlier in this review, MSW is assumed/considered mainly as the solid refuse, debris, or waste produced within the boundary of a district as well as the municipality, irrespective of where it is generated. In the city or urban class, it is divided into two subdivisions, that are generated from the residential area (habitable) and non-residential area (commercial/business district, corporate institutions/services building construction/demolition, and special/others) (Osinowo et al., 2018). Thus, the special classification comprises the special groupings that represent different groups based on the raw material used in production/business activities, due to the services they render, or because of the goods they trade, have the potential to produce hazardous solid waste that could be deleterious to human health or the well-being of the environ. The next category is the industrial type, which comprises all facilities, that generate such solid waste irrespective of their size, and location, and is generated from a unit of industrial type. Lastly, the rural category encompasses all solid waste that is generated from agricultural and animal-keeping management.

## 3. Waste legislation and regulations

The legislation and regulations that govern the MSW differ from one country to the other. The different countries are responsible for making acceptable legislation and regulations that will be humanly and eco-friendly in waste management. However, in the global context, the legislation and regulations have been developed from the simplest and unofficial terms to more complicated and formal waste management legislation and regulations. As sustainability in waste management has been echoing persistently worldwide, other concepts such as source reduction, waste reduction, and attainment of sustainable methods of production as well as consumption were included in the waste management system/process (Rossi et al., 2020). The legislation and regulations in waste management have lately taken a new dimension as more focus is on the protection of the environment from the global perspective to strengthen and maintain sustainable development.

Among the commonest and most popular regulations is contained in Agenda 21, which was approved in 1992. It aimed to address the shortcomings associated with sustainable waste management globally during the United Nations Conference convened to deliberate on the Environmental and Development. Several legislation and regulations are in existence globally but there are limitations on the resource to exploit for a better reporting of such legislation and regulations. The legislation on waste management is mostly enacted with the sole objective of protecting the environment and the health of the populace via the forestallment/bar/safeguard of the deleterious impacts of hazardous, non-hazardous, and inert waste generation and general management of such wastes (EU, 2008). However, the European Union (EU), Japan, Malaysia, and several other countries of the world have enacted different legislation to address the excesses of humans in generating and managing the wastes in more eco-friendly and sustainable ways. As a case study, the existing legislation among the EU countries, Japan, and Malaysia are shown in Table 1.

## 4. Evolution of solid waste management

The municipal solid waste management is concerned with the generation of waste, monitoring/regulation, storage within the source, collection, transportation/movement/evacuation, processing, and disposal of the solid waste to the final destination mostly in the landfill following the legislation, health regulations, and the economic framework to attain environmental sustainability (Al-Maaded et al., 2012). Generally, the impact of solid waste on the environment and human existence are noticeable in the folds namely direct and indirect impacts respectively. Indeed, the direct impacts, are associated with the degradation of solid materials and damage to human health. The indirect impacts on their own are everlasting impacts that could affect the ecosystem patterns and the problems of climate change, which subsequently determine the structure of society, economics, and the sustainability of the respective continents (Al-Maaded et al., 2012; Zafar, 2015, 2017). Gulf Cooperation Council (GCC) countries including the Kingdom of Saudi Arabia, United Arab Emirates, Oman, Al-Kuwait, Qatar, and Bahrain, are faced with issues regarding municipal solid waste management resulting from the persistent high population rise, rise in social engagement, and economic development and expansion (Al-Jarallah and Aleisa, 2014; Arafat et al., 2015). Interestingly, the state of Qatar known as one of the fasted growing economies globally is not exempted from these challenges and it has been experiencing fast industrialization, persistent population growth, and accelerated urbanization that leads to a rise in waste generation.

The average MSW generation rate per capita in the GCC reaches 1.5 kg/person/day during the past years (Hahladakis and Aljabri, 2019). The estimated daily produced solid waste in Qatar stands at 28,000 tons/day, which is disposed of through three methods viz. recycling, incinerating, and the leftover is sent to the landfills. Furthermore, the recycling parts are mainly household and commercial waste that often constitutes the larger portion of waste generated. However, it was forecasted that by 2032, the volume of total domestic waste would rise to 19,000 tons per day with the exclusion of C&D waste and others. Nonetheless, the 4.2% annual growth experienced is an indicator that the population of Qatar is growing steadily as her economies increase (Ayoub et al., 2014; Qatar Development Bank, 2013).

The country has taken several drastic measures to ensure environmental sustainability by mitigating the impacts of extreme rise in population size and massive economic growth may have on Qatar's environmental system through various plans and policies (Meza et al.,

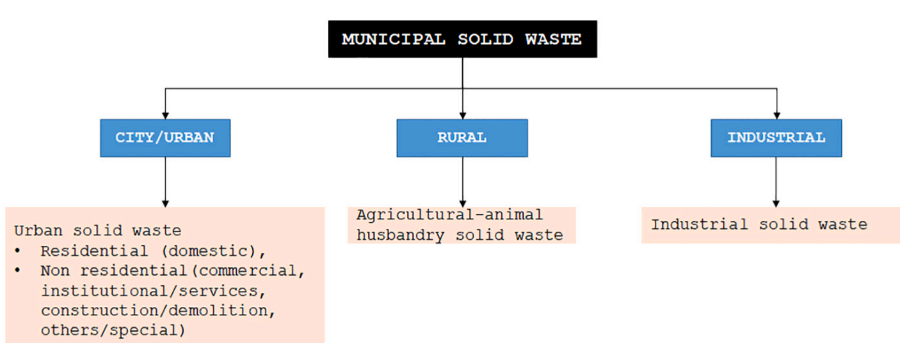


**Fig. 1.** The schematic drawing showing the classification of municipal solid waste (modified from Buenrostro et al., 2001).

**Table 1**
Existing legislation with the enacted and amended in EU, Japan, and Malaysia.

| EU | | | Japan | | | Malaysia | | |
|---|---|---|---|---|---|---|---|---|
| Legislations | Enacted | Amended | Legislations | Enacted | Amended | Legislations | Enacted | Amended |
| EU Directive 2008/98/EC | 1975 | 1991, 2008 | Waste Management and Public Cleansing Law (WMPC) | 1970 | 2021 | Solid Waste and Public Cleansing Management Act 2007 - with additional advantage to promulgate more legislation (41) | 2007 | Nil |
| The packaging and packaging waste - Directive 94/62/EC | 1994 | | Promotion of Effective Utilization of Resources | 1991 | | | | |
| The integrated pollution prevention and control - Directive 96/61/EC | 1996 | | Law for Containers and Packaging Recycling | 1995 | | | | |
| The landfill of waste - Directive 1999/31/EC | 1999 | | Law for Home Utensils/ Appliances Recycling | 1998 | | MSW waste reduction, reuse, and recycle | | |
| The incineration of waste - Directive 2000/76/EC | 2000 | | Establishing the Recycling-Based Society Basic Law | 2000 | | | | |
| The end-of-life vehicles - Directive 2000/53/EC | 2000 | | Law for Construction Materials Recycling | 2000 | | Utilization of recyclable environmentally friendly materials | | |
| The electrical waste and electronic equipment - Directive 2002/96/EC | 2002 | | Law for Food Recycling | 2000 | | | | |
| | | | Promoting Green Purchasing Law | 2000 | | | | |

2019). The emergence of the National Development Strategy (NDS) serves as another policy direction to tackle issues with higher national priorities. One of such priorities is the proposed attainment of a solid waste management plan giving recycling a priority. In this regard, the landfills are targeted to be reduced to as much as 53% while focusing more on recycling, which is expected to rise from 8% to 38% of solid waste (Al-Muhannadi, 2013). Consequently, the leftover waste has been converted to energy for different uses.

Markic et al. (2019) provided scientific support to municipal waste management by using material flow analysis for waste management planning. They developed two scenarios and two sub-scenarios, namely Scenario S0, which represents the current method of MSW management

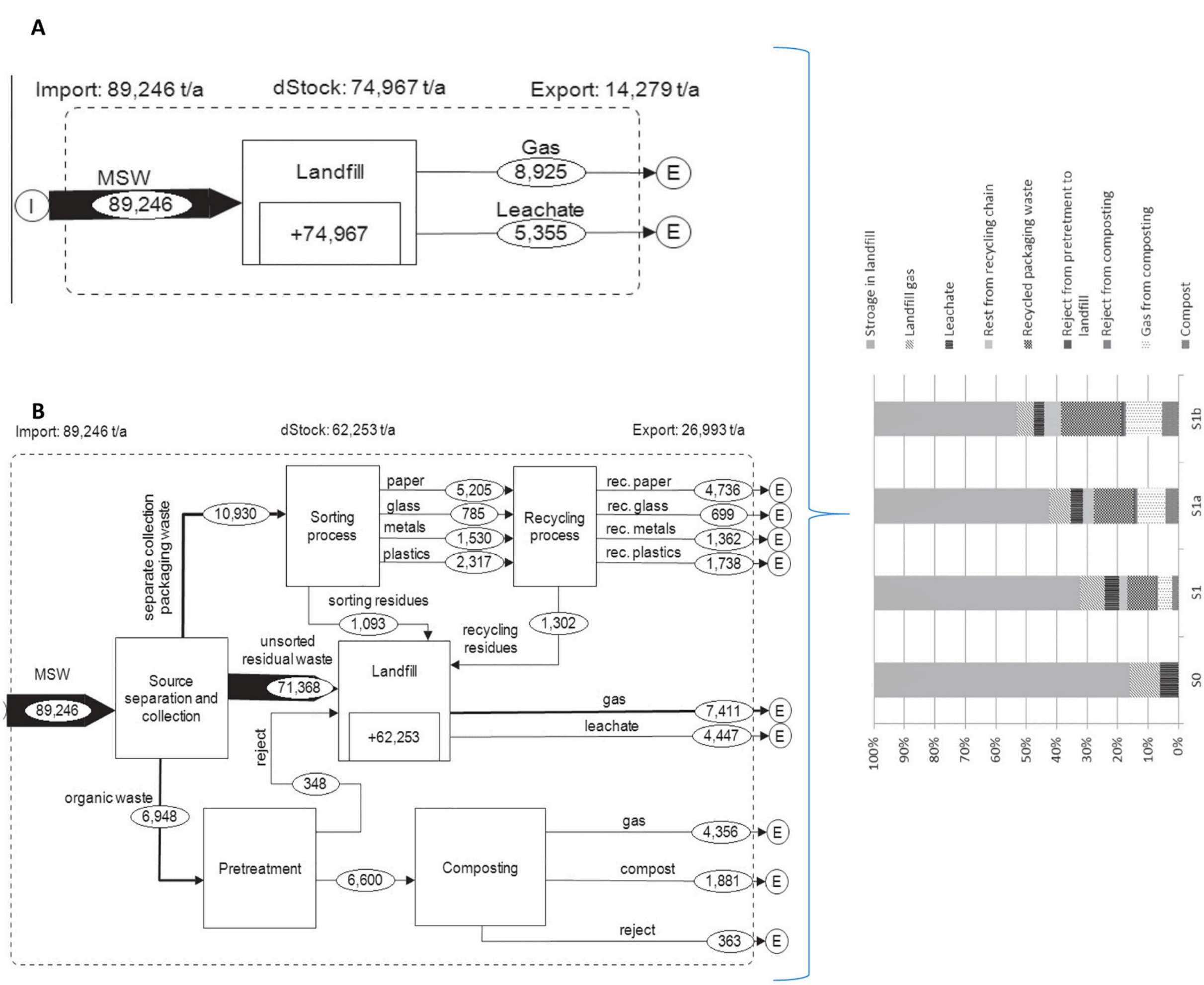


**Fig. 2.** Material flow analysis of waste management system for A. scenario S0 and B. scenario S1 (Markic et al., 2019).

in the Banja Luka region, Scenario S1, which implies the separation of waste at the source, and in households (25% of organic waste and 25% of packaging waste). Within scenario S1, two sub scenarios were also established. Scenario S1a includes the separation of waste at source in households or as in the previous scenario (50% of organic waste and 35% of packaging waste), and Scenario S1b, which implies the separation of waste at source and in households, as in scenario S1 (65% of organic waste and 55% of packaging waste) as shown in Fig. 2.

Moreover, Midgley et al. (2021) studied the systems-engineering approach to nation-scale problems of municipal solid waste management in Saudi Arabia. The behavior and effects of the system under different interventions were investigated through a narrow system of interest (NSOI) and a detailed system context diagram for the NSOI as represented in Fig. 3.

## 5. Waste remediation, treatment, and disposal

The waste-related pollution in the soils, water surface as well as groundwater exposes humans to a huge health hazard (Al-Ghouti and Dib, 2020). Thus, the methods and technologies applicable/to be used in remediation are very important to achieve a complete cleaning, elimination, containment, reclamation as well as restoration of a polluted environment. Moreover, different studies have conducted investigations to establish the effectiveness of materials and methods for water remediation that could be extended to the other contaminants in the environment. Such methods include but are not limited to electrochemical treatment, flocculation/coagulation, and aerobic and anaerobic treatments (Al-Ghouti and Dib, 2020). By default, before choosing a remediation method for any polluted soil/environment the site survey must be conducted and an understanding of all the associated parameters viz. the chemical, physical, and biological constituents of the pollutants for a better result. In addition, the budget, regulatory framework, and the existing policies are essential factors to be painstakingly analyzed before venturing into the selection of any remediation method. Interestingly, environmental scientists have resorted to the use of risk-based strategies in curtailing environmental pollution and remediating in case the environment is contaminated. This measure is essential as the rate of environmental pollution is increasing that requires speedy intervention.

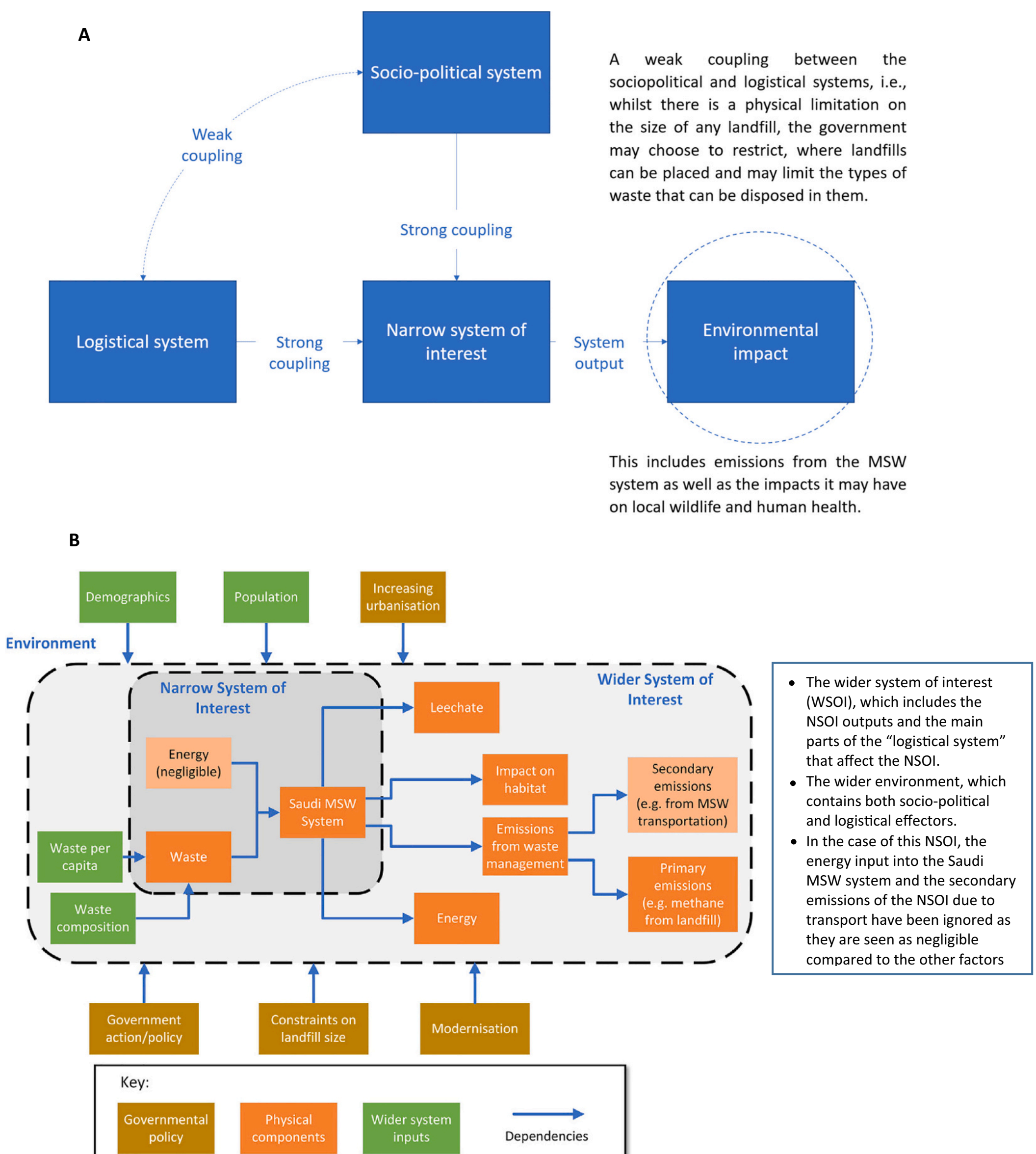


**Fig. 3.** A. High-level system interaction overview, B. System context diagram C. Schematic overview of Saudi MSW model (Midgley et al., 2021).

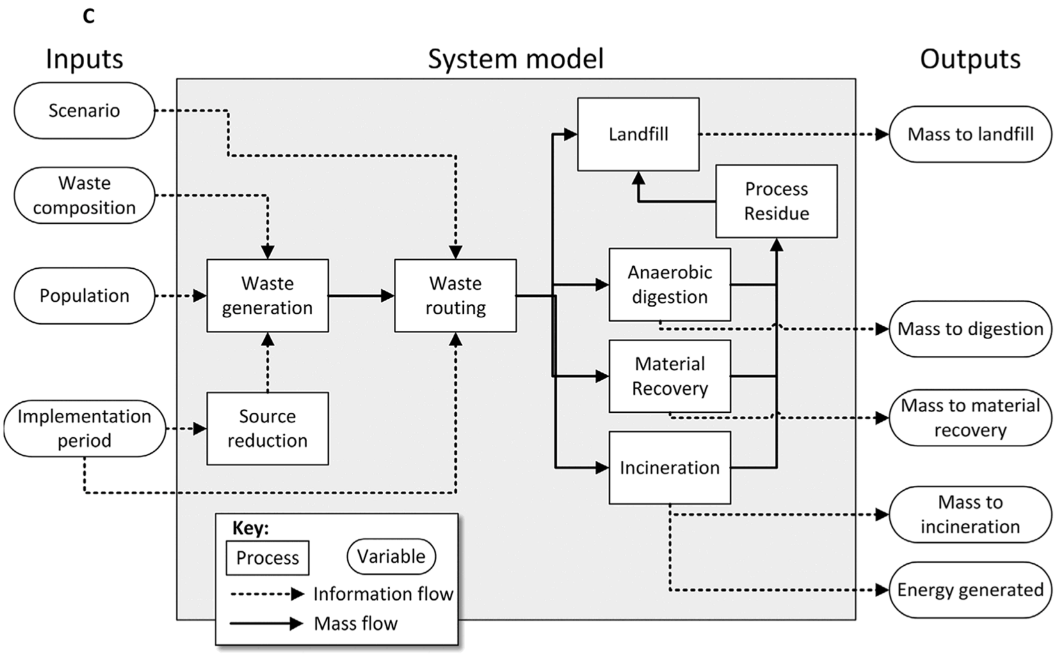


**Fig. 3.** (*continued*).

### 5.1. Landfills and incineration

#### 5.1.1. Landfills technology

While landfill provides cheap and simple waste disposal means, they can potentially lead to negative consequences on the entire ecosystem including species at the highest trophic level if not properly managed. This is largely due to the release of various kinds of contaminants in liquids, dust, and gaseous forms (Ferronato and Torretta, 2019). Wastes are indiscriminately dumped in many countries especially developing nations before the enactment of regulatory guidelines and procedures with no consideration for the potential effect of leachates generation and or gas emission into the atmosphere (Aderoju et al., 2020). As a result, there have been repeated calls by the public in many quarters around the world on the need to improve waste management and hence the interest of scientists and stakeholders alike to act (Bert et al., 2012). Nonetheless, public concerns about landfill-contaminated sites include gaseous emissions, and soil and underground water contamination, which eventually negatively affect human health (Kim and Owens, 2010; Bert et al., 2012; Mukherjee et al., 2015). Generally, landfills are classified into two categories namely, open landfills and sanitary landfills (Al-Ghouti et al., 2020). The open type is very predominant in operation and is constructed in a manner to permit the free movement and exchange of gaseous and liquid molecules between landfill facilities and the environment (Osinowo et al., 2018). Contrarily, sanitary landfill segregates the waste from the surrounding. The major demerit of this type of landfill is the probable failure in the linear system efficacy. While on the other hand, sanitary isolates the refuse, debris, and waste from the environment. Thus, the main limitation of this type of landfill has to do with the problem associated with good performance viz. linear system efficiency (Feng et al., 2020).

Until recently when it was recognized that contaminants partition the adjacent environmental compartments, landfill sites are mostly a collection of non-closed dumped refuse, where the surrounding soil and water were highly contaminated (Iravanian and Ravari, 2020). Reports have clearly shown the hazardous nature of such contaminants and the health risk it portends to living organisms including humans (Abiriga et al., 2020). Contaminants and the extent of negative effects depend on the source of the materials in landfill sites which are broadly categorized into three groups according to their sources, and as shown in Table 2 (Al-Maaded et al., 2012), different landfill sites cause different environmental problems (Mohammadi et al., 2019). The reference waste for this review is municipal solid waste, which normally consists of a large amount of organic matter, transformed by microbes, and ends up in groundwater and the atmosphere via leachate and emission (Kumar and Alappat, 2005). Intriguingly, a consolidated landfilling can be of economic value when the generated byproduct as gas viz. landfill gas and leachate gas are put into domestic and industrial uses to generate income (Kasassi et al., 2008). The landfill and leachate can be integrated. Thus, recycling and upgrading the landfill gas to biogas is characterized by its combustibility and it generates flare with dual benefits of producing heat as well as power (Fig. 4). Nonetheless, with adequate management of landfill technology, there is the probable benefit of the transformation of these landfills from their initial form as “waste storehouses” to “energy powerhouses” that will subsequently generate sustainable energy for both domestic and industrial consumption (Nanda and Berruti, 2020).

**Table 2**
Municipal solid waste generation and composition in the Arabian Gulf countries compared to the USA and the UK (Al-Maaded et al., 2012).

| Country | Organic (%) | Paper (%) | Plastic (%) | Glass (%) | Metals (%) |
|---|---|---|---|---|---|
| Qatar | 57 | 11 | 14 | 4 | 9 |
| Bahrain | 59.1 | 12.8 | 7.4 | 3.4 | 2.1 |
| Kuwait | 51 | 19 | 13 | 4.5 | 5 |
| Oman | 60 | 8 | 12 | 10 | 9 |
| UAE (Dubai) | 42 | 6 | 10 | 3 | 3 |
| Abu Dhabi | 49 | 6 | 12 | 6 | 6 |
| USA | 11.2 | 37.4 | 11 | 8 | 8 |
| UK | 20 | 7 | 7 | 10 | 10 |

#### 5.1.2. Gas emission

Although carbon dioxide and methane constitute about 60% of the gas emission from contaminated landfill sites (Nikiema et al., 2005), other gases such as “carbon monoxide, nitrogen, oxygen, hydrogen as well as hydrogen sulfide are also common in variable proportions and are considered hazardous to the environment (Nagendran et al., 2006).

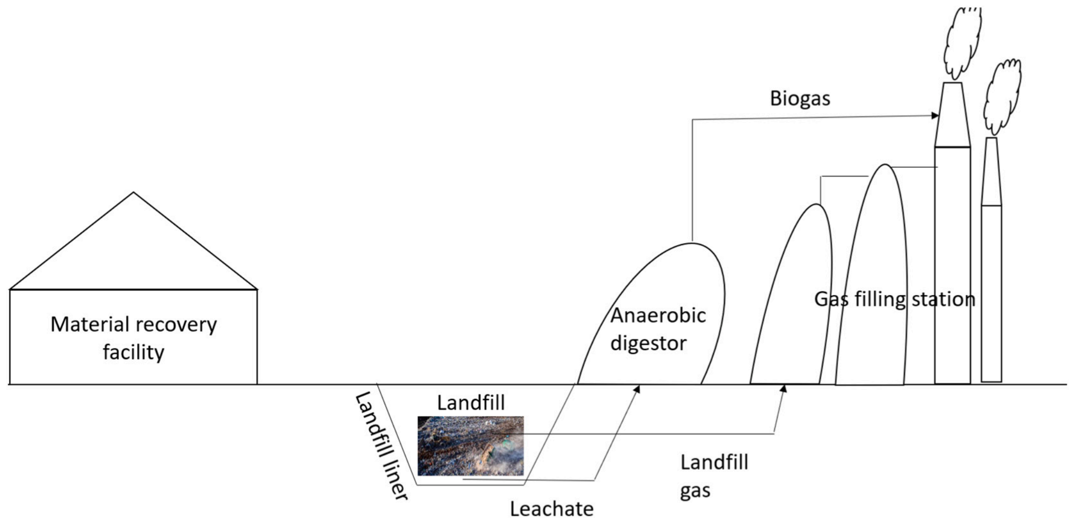


**Fig. 4.** Maximization of municipal solid waste process and the usage of byproducts viz. leachate and landfill biogas for power generation. The system is advantageous as it can enhance the sustainable management of domestic waste by converting it to clean energy.

Indeed, carbon dioxide and methane have been established as greenhouse gases and contribute to climate change, 15% of methane greenhouse gas originates from landfills (Rawat et al., 2008; Ritzkowski and Stegmann, 2007). Although methane was reported to be non-toxic to plants, gas emissions from landfill sites are of adverse effects on plants grown to vegetate contaminated sites, for instance, following the degradation of landfill wastes, oxygen replaced by methane and carbon dioxide results in "asphyxia of plants" (Vaverkova, 2019). On the other hand, the concentration of carbon dioxide in the soil is less than 2% and plants were reported to thrive well in concentrations below 5%, however, at a higher concentration of more than 20%, carbon dioxide is said to be phytotoxic (Nagendran et al., 2006). Notwithstanding, the sufficiency of oxygen in the soil, carbon dioxide is generally high in concentration at landfill sites and could be toxic to surrounding plants especially to more vulnerable tissue, the roots (Eskandari et al., 2012).

#### *5.1.3. Leachates*

Landfill leachate is any form of liquid waste composed of non-desirable substances percolated through tons of waste and emit within a landfill site (Ikehata and Li, 2018). In other words, landfill leachates form by the degradation of organic components of landfill wastes and are moved by an aqueous phase through the soil (Koga et al., 2011). Leachate is potentially a high polluting liquid as it is composed of elevated levels of organic and inorganic chemicals, organic matter both dissolved and suspended as well as heavy metals (Ziyang et al., 2009). Additionally, high biological and chemical oxygen demands are also characteristics nature of leachate, which eventually partitions the soil and underground water phase and poses serious environmental problems (Gajski et al., 2011).

Hazardous chemicals in the region of two hundred species were reported in a complex mixture of landfill leachate, these include "phenols, pesticides, halogenated compounds, polyaromatic hydrocarbons, ammonium, and heavy metals" (Mukherjee et al., 2015). These pollutants threaten the aquatic biota as well as the food chain which in turn negatively affects public health and causes severe health issues including carcinogenicity and genotoxicity (Chu et al., 2019). Landfill leachate is characterized based on basic parameters such as pH, suspended solids (SS), chemical oxygen demand (COD), biological oxygen demand ($BOD_5$), $BOD_5$/COD ratio, ammonium nitrogen ($NH_4$-N), total Kjeldahl nitrogen, and heavy metals (HMs) (Kulikowska and Klimiuk, 2008). The landfill age significantly affects the concentration of organics, leachate concentration, and degradability, which decreases with age. Often, younger leachates are composed of low molecular weight compounds whereas older ones bear larger molecular weight compounds while ultra-high resolution mass spectrometry is used for the molecular characterization (Martin et al., 2021).

Unlike before, different technologies for landfill leachate treatment have been discovered to comply with the various existing legislation for achieving and maintaining standards. Interestingly, the treatments of landfill leachates could be executed through methods such as biological processes, physical-chemical processes, membrane filtration, and advanced oxidative treatments among others (Talalaj et al., 2019). The appropriate method to be used has been greatly influenced by the organic composition and when this is high to the tune of over $1.0 \times 10^4$ mg/L, biological treatment is the best approach. Similarly, if the landfill leachate is high in ammoniacal nitrogen concentration and has low biodegradable potential, then the appropriate approach to go for is a physical-chemical process. In the same line, the respective age of the leachate have a lot to do in determining the appropriate treatment method to use. Generally, the ages are classified as young (less than five years), medium (5 years–10 years), and old (greater than 10 years).

#### *5.1.4. Transport and fate of contaminants in leachates*

Organic pollutants in form of hydrocarbons normally are subjected to biodegradation by the activity of soil microorganisms in the vadose layer, resulting in the production of carbonic and organic acids known to improve dissolved minerals in the soil (Lipinska et al., 2021). As a consequence, high total dissolved solids (TDS) and leachate plumes are formed (Atekwana et al., 2000). Several studies have established that plumes of leachates are formed from landfill sites, which migrate to the subsurface aquifers to form an even bigger plume (Sultana et al., 2017). Various other studies were conducted to investigate the migration process through the landfill (Lu et al., 2011; Varank et al., 2011), and by consensus, two distinct transport routes of leachates were suggested by a group of scientists (Foose et al., 2002; Katsumi et al., 2001). The first was advection and dispersion of pollutants through the soil membrane when in defective conditions, while the second involved the transport of organic pollutants by diffusion through the soil membranes. Chofqi et al. (2004) reported that several factors could influence the transport of these organic contaminants and their migration to underground water. These include leachate stability, soil permeability, unsaturated zone, water depth, infiltration, and humidity.

Leachate plumes are usually composed of high concentrations of volatile organic carbon such as fulvic acids (FA), ammonium, and various xenobiotic chemical compounds including benzene, toluene, ethylbenzene, and xylene (BTEX), phenols as well as chlorinated compounds that are widely distributed (Siddiqi et al., 2021). Leachates plume generation both in terms of quality and quantity varies with season alongside seasonal factors, which include but are not limited to temperature, humidity, solid waste composition and moisture, precipitation, and population densities (Mukherjee et al., 2015). The migration of pollutants largely depends on the composition of the leachate or the water partitioning contaminant itself. Leachates are a complex mixture of compounds and pollutants, and similar chemical pollutants may behave in the same fashion due to the influence of co-contaminants in a mixture (Abu-Rukah and Al-Kofahi, 2001).

### 5.2. Incineration

Incineration as a waste management method is not as sustainable as landfill technology because it requires higher energy consumption (Nanda and Berruti, 2020). Municipal solid waste (MSW) incineration is more popular and generally acceptable because is characterized by volume reduction and energy trapping for power generation (Lu et al., 2017; Nanda and Berruti, 2020). Incineration technology in managing MSW has increased tremendously in recent times simply because there is a corresponding increase in the MSW generation that requires adequate management (Lu et al., 2017). Nevertheless, the expansion of the application of the use of incineration technology has attracted complaints from the public and in most cases attracted the staging of protests against the use of incineration technology. Many countries of the world experience such criticisms and protests namely, the U.S. (Ni et al., 2009), South Korea (Johnson, 2013a,b), and Ireland (Wagner-Döbler, 2013; Johnson, 2013a,b; Wong, 2016). However, in 2015, there are 1179 incineration plants globally with the ability to generate a substantial amount of power that can reach a total volume of over 700,000 Mg/day (Mg stands for Megagram which equals a metric ton) as illustrated in Table 3. Furthermore, it is peculiar for an incineration facility/plant to involve more than two incinerators on average depending on the availability of the resources. Also, virtually all the regions settle for optimum operation of the incinerators by ensuring that the capacity of the incinerator in use exceeds 200 Mg/day while the plant operation capacity should close and exceed 400 Mg/day, thus leading to better thermal efficiency and putting potential pollution under utmost check. Generally, the efficacy and the operative performance of any incinerator must be known to ascertain if it is running perfectly well and is determined through the utilization rate.

$$\text{Utilization rate } (\%) = \frac{\text{Amount of MSW incineration}}{\text{design capacity}}$$

where 8000 operating hours/annum is considered as the benchmark.

However, when the value of utilization rate is small, it implies that the incinerator operation is not maximized/optimized probably due to instability operation, shortage of input, or disruption of operational capacity. Interestingly, a study conducted by Al-Ghouti et al. (2020) mentioned that the by-product or combustible residuals from incineration such as municipal solid waste bottom ash (MSW-BA) and fly ash (MSW-FA) are a good source of aluminosilicate to produce geopolymer (GEO) adsorbents (GEO-MSWBA and GEO-MSWFA) for water purification to enhance the removal of methylene blue (MB) from water.

### 5.3. Energy flux through landfill and incineration MSW

The quantity of energy intake and release concerning the chosen system is obtained from the evaluation of the energy movement that is considered as the number one priority to achieve the maximum result. Quantitatively, they are obtainable by finding the product of the quantity of energy input expressed as a standardized coefficient of the energy inflow and outflow in the incineration and landfilling activities as a reflection of the energy cycle of the process (Table 4). By default, the estimation or quantitative values are obtained from the data evaluation and the result is being expressed in standard unit gigajoule (GJ) through a simple conversion (8500 t MSW)$^{-1}$. Interestingly, the resources are classified into incineration and landfilling process as output and input, respectively. Input is considered as the resources consumed or utilized by these processes, which include but are not limited to petrodiesel, human effort, human capital, transportation, and electricity while the output includes electricity, biogas, and biosludge that could be used as inputs in another process.

However, considering the few challenges associated with incineration and landfilling processes or systems of MSW, it has been established that the best way to analyze their associated energy both the inflow and outflow is to apply the energy indicator. Four indicators of such are commonly used known as the energy ratio or energy use efficiency,

**Table 4**
The energy equivalent of resource inputs and output in waste management processes (Nabavi-Pelesaraei et al., 2017).

| Resource(s) | Unit | Energy equivalent (GJ unit$^{-1}$) | References |
|---|---|---|---|
| 1. Input | | | |
| a. Human effort (hour) | h | 0.00196 | (Peyman and Ashkan, 2014) |
| b. Petrodiesel (L) | L | 0.05331 | (Singh, 2002) |
| c. Transportation | t*km | 0.0045 | (Tabatabaeefar et al., 2009) |
| d. Electricity | kWh | 0.01193 | (Ashkan et al., 2014) |
| 2. Output | | | |
| a. Electricity | kWh | 0.01193 | (Ashkan et al., 2014) |

**Table 3**
An overview of MSW incineration around the globe (modified from Lu et al., 2017).

| Region | Number | | To. Cap. Mg/d | Av. Cap. Mg/d | | Incineration (103 Mg/a) | Utilization rate (%) |
|---|---|---|---|---|---|---|---|
| | Plants | Incinerators | | Plants | Incinerators | | |
| China (2015) | 268 | 552 | 231,600 | 864 | 420 | 61,755 | 80 |
| EU (2012) | 469 | 917 | 207,104 | 442 | 226 | 59,023 | 85 |
| Denmark | 29 | 64 | 10,900 | 376 | 170 | 2307 | 63 (99) |
| France | 127 | 248 | 45,334 | 357 | 183 | 11,951 | 79 |
| Germany | 79 | 192 | 52,554 | 665 | 274 | 17,192 | 98 |
| Italy | 52 | 97 | 17,825 | 343 | 184 | 5529 | 93 |
| Japan (2013) | 234 | 551 | 92,203 | 394 | 167 | 33,729 | 110 (59) |
| Netherlands | 13 | 42 | 18,660 | 1435 | 444 | 4515 | 73 |
| South Korea (2013) | 39 | 72 | 13,580 | 348 | 189 | 4475 | 99 |
| Sweden | 34 | 67 | 14,477 | 426 | 216 | 2233 | 46 (98) |
| Taiwan area (2006) | 24 | 62 | 24,650 | 1027 | 398 | 4036 | 49 |
| U.S. (2014) | 80 | 210 | 88,765 | 1110 | 423 | 29,665 | 100 |
| Other regions (2013) | 65 | 144 | 49,903 | 768 | 347 | – | – |
| Total | 1179 | 2508 | 707,805 | 600 | 282 | – | – |

energy productivity. It estimates the amount of energy produced or given, the next is a specific energy, and lastly, net energy - the difference between the output/outflow energy and the total input/inflow energy all expressed in the standard unit; gigajoule (GJ) (Ashkan et al., 2016).

Mathematically,

$$\text{Energy use efficiency} = \frac{\text{Output energy}\left[\text{GJ}\left(8.5 \text{ x } 10^3 \text{ t MSW}\right)^{-1}\right]}{\text{Total input energy}\left[\text{GJ}\left(8,500 \text{ t MSW}\right)^{-1}\right]} \quad (1)$$

$$\text{Energy productivity} = \frac{\text{Electricity}\left[\text{GJ}\left(8.5 \text{ x } 10^3 \text{ t MSW}\right)^{-1}\right]}{\text{Total input energy}\left[\text{kWh}\left(8.5 \text{ x } 10^3 \text{ t MSW}\right)^{-1}\right]} \quad (2)$$

$$\text{Specific energy} = \frac{\text{Total input energy}\left[\text{GJ}\left(8.5 \text{ x } 10^3 \text{ t MSW}\right)^{-1}\right]}{\text{Electricity}\left[\text{kWh}\left(8.5 \text{ x } 10^3 \text{ t MSW}\right)^{-1}\right]} \quad (3)$$

$$\text{Net energy} = \frac{\text{Output energy}\left[\text{GJ}\left(8.5 \text{ x } 10^3 \text{ t MSW}\right)^{-1}\right] - \text{Total input energy}\left[\text{GJ}\left(8.5 \text{ x } 10^3 \text{ t MSW}\right)^{-1}\right]}{1} \quad (4)$$

## 6. Composting of organic solid wastes

Organic waste as a fraction of MSW, which includes food debris, agricultural wastes, yard debris, and process wastes, forms the largest part (46%) of the total solid waste generated (Hoornweg and Bhada-Tata, 2012). Thus, effectively managing the organic solid waste to attain management sustainability is very essential to achieving an acceptable standard of disposing of solid waste in an environmentally friendly way (Lohri et al., 2017).

Composting is another reliable waste disposal method, particularly for domestic waste that is considered organic. Thus, composting stands as the most available opportunity to recover material from the organic component of municipal solid waste as it can be reused in the form of a biofertilizer to enhance soil fertility (Cesaro et al., 2015). In addition, it has been widely accepted because of the low operation cost as well as high social and environmental advantages (Lim et al., 2016; Onwosi et al., 2017). Nonetheless, composting is the process of subjecting organic matter to biological degradation under-regulated aerobic conditions to produce a biologically stable end product (Lim et al., 2016). Such material should be devoid of oxygen consumption and not capable of generating metabolites that are phytotoxic in nature (Zhang et al., 2016). The composting process is facilitated by the rigorous activities within the microbial community where degradable organic matter is converted to a relatively stable, humified form with water, carbon oxide as well as ammonia gas (Li et al., 2014; Cesaro et al., 2015; Zhang et al., 2016).

Nevertheless, composting exhibits other merits over other methods of waste management as it promotes waste volume reduction, unwanted plant (weed) seed destruction, and ruination of pathogenic bacteria (Xiao et al., 2017). But despite these merits, composing could be disadvantageous in several ways that include the release of nitrogen through ammonia gas ($NH_3$) by volatilization (Sánchez-García et al., 2015), emission of greenhouse gases (GHGs) such as methane ($CH_4$), and dinitrogen oxide ($N_2O$) (Lim et al., 2016). As well as the environmental threat from the possible release of inorganic/organic pollutants that is mostly inevitable from compost substrates (Sánchez-García et al., 2015; Lim et al., 2016; Martinez-Sanchez et al., 2017; Onwosi et al., 2017). Therefore, several measures are considered to mitigate these limitations in composting viz. the adoption of different aeration methodologies, application of bulking agents, and condition of substrate/feedstock formulation to guarantee optimum conditions for a sustainable composting process (Martín-Marroquín and Hidalgo, 2014; Onwosi et al., 2017; Xiao et al., 2017). However, compost must attain a defined standard to be considered safe and qualified and to be used in the soil as a biofertilizer. In most countries of the world especially in Europe, there are concise, explicit, and detailed rules promulgated by legislation as the subset of waste law (Table 5).

## 7. Pollutant partitioning

The transport of pollutants through the atmosphere, water, and soil is of important concern because of the deposition and bioaccumulation of mostly organic compound pollutants in the aquatic ecosystem after being leached through landfill processes/operations. Hence, all relevant environmental factors should be quantified to describe a particular process and understand and evaluate the dynamic behavior and principles of transport of a given pollutant in the environment. It has been proved that several partitioning viz. air to liquid, solid to liquid partitioning affects the fate and movement of gas molecules and compounds between one phase and another (Amos et al., 2012). It is well established that while the organic pollutants are leached readily from the landfill, the deposition process fluctuates and is influenced greatly based on the phase. Consequently, it is essential to know the behavior and propensity of the organic pollutant to either retain it in the solid phase (Rutter and Schauer, 2007a,b). Conventionally, many organic compounds are characterized as hydrophobic, which makes them insoluble in water; this is very easy to eliminate them from the aqueous phase via particle removal. Interestingly, aside from the usual aqueous and particulate phase, adsorption of the organic compound could be extended to colloids and is often regarded as "the third phase". In addition, studies have indicated that hydrophobic compounds are likely to cling to hydrophobic colloids in different phases viz. marine ecosystem, groundwater, and soil (Kalmykova et al., 2013). This consequently/thus/subsequently revealed from the analytical value of synthetic solutions as regards the impact of dissolved organic carbon (DOC) that reduced/minimized partitioning of hydrophobic pollutants to the solid phase. Generally, solvent/organic partitioning is expressed as the concentrations in each phase without attaining the saturation boundary of the system. Usually, the data are linear which can be expressed from/by the equation below:

$$\frac{C_1}{C_2} = K_{12} \quad (5)$$

where $K_{12}$ is the slope of the curve i.e. $K_{12} = \frac{C_1}{C_2}$

Moreover, $C_1$ and $C_2$ are different concentrations in the solvent/organic phase, respectively (Al-Ghouti and Dib, 2020). Interestingly, the process of partitioning could be understood in another way by thinking of the mobility of chemical molecules from one phase to another owing to the discrepancy in solubility in all the media (Al-Ghouti and Dib, 2020). Therefore, at equilibrium concentrations in each phase or compartment are stable, thus the computation of the partitioning coefficient can be obtained as a function of solubility as shown in the equation:

**Table 5**
Compost criteria for its qualification as product/waste in the different European Member States (Cesaro et al., 2015).

| Country | Compost status | Criteria for the definition of compost status and its use on soil |
|---|---|---|
| Austria | Product | – Production in a registered plant; – Origin from specific input materials; – Documented life cycle (from waste reception to product selling). |
| Flanders (Belgium) | Product | Requirements on: – Input materials; – Process conditions; – Product characteristics and use. |
| Wallonia (Belgium) | Waste | Among the four classes (A–D) defined by the Government Decree, compost belongs to class B and can be used on/in agricultural soil. Within class B, subclasses B1 and B2 are distinguished. The main difference lies in the acceptable metal content. |
| Czech Republic | Product | Need for registration as “One Compost Class” based on the inspection/control of samples performed by the Control and Testing Institute for Agriculture. |
| Denmark | Waste | Possibility of using for agricultural purposes, with a strict limit on heavy metal content applied to the soil. |
| Finland | Waste/ product | Defined as waste under the Waste Act, compost turns into a product if the requirements of the fertilizer regulations are fulfilled. |
| France | Waste/ product | Requirements of the NF U 44-051 Standard must be fulfilled. If not, compost is considered waste. |
| Germany | Waste | Requirements established by the bio-waste Ordinance. Voluntarily, if certified under the QAS of the RALGZ 251, compost can be put on the market and used as a PRODUCT. |
| Greece | Product | Requirements of the Specifications and General Programs for Solid Waste Management need to be fulfilled for the compost to be sold. |
| Hungary | Waste/ product | Requirements of the Statutory Rule 36/2006 (V.18) must be fulfilled. If not, compost is considered waste. |
| Ireland | Product | On-site-specific waste license or waste permit must be fulfilled. |
| Italy | Waste/ product | Requirements of the Legislative Decree 75/2010 must be fulfilled for compost use as fertilizer. If not, environmental restoration applications can be considered, when limit values of Inter-ministerial Decree 27/7/84 are fulfilled. Otherwise, compost is considered waste. |
| Latvia | Product | Requirements on hygienic properties pollutant potential must be certified by acknowledged laboratories. |
| Lithuania | Product | Certificate on compost quality provided by the producer, without external approval and/or inspection. |
| Luxembourg | Product | Fulfillment of quality assurance system based on: – Input materials characteristics; – process operating conditions; – product properties (pathogens, heavy metals) and labeling. |
| The Netherlands | Product | – Process and its documentation; – Product properties, including stability (no limit value!); – Declaration and labeling. |
| Poland | Waste/ product | According to the Waste Law/Fertilizer Law |
| Portugal | Product | Considered as a soil amendment under the Fertilizer Law |
| Slovakia | Product | – Process operating conditions; – Product qualitative characterization; – Certification by acknowledged laboratories/institutes |
| Slovenia | Waste/ product | Requirements of the Decree on the treatment of biodegradable waste must be fulfilled. If not, compost is considered waste. |
| Spain | Product | – Origin from specific input materials; – Documented life cycle (from waste reception to product selling); – Requirements for compost qualitative characterization. |
| Sweden | Waste | Standard defined by the Swedish Standardization Institute. |
| UK | Waste/ product | Depending on the case-by-case decision, based on the possible agricultural benefit. When considering a product, standard certification protocols are followed. |

**Table 6**
Factors affecting the adsorption capacity of microplastics (MPs) (modified from Fu et al., 2021).

| | Influencing factors | Effect | Adsorption capacity |
|---|---|---|---|
| Physicochemical properties of MPs | SSA ↑ | Adsorption sites ↑ | Positive effect |
| | Particle size ↓ | SAA ↑ | Positive effect |
| | | Agglomeration ↑ (SSA) ↓ | Negative effect |
| | Aging ↑ | SSA ↑ | Positive effect |
| | | Hydrophilicity ↑ | Negative effect (for HOCs) |
| | Crystallinity ↑ | Free volume ↓ | Negative effect |
| | Functional group ↑ | II-II interaction ↑ | Positive effect |
| | | Hydrogen bonding ↑ | Positive effect |
| | | Halogen bonding ↑ | Negative effect |
| | Polarity ↓ | Hydrophobicity ↑ | Positive effect (for HOCs) |
| Properties of organic pollutants | Hydrophobicity ↑ | Hydrophobic interaction ↑ | Positive effect |
| | Ionic properties ↑ | Electrostatic interaction ↑ | Positive effect |
| | | Electrostatic repulsion ↑ | Negative effect |
| Environmental factors | Temperature ↑ | Surface tension ↓ | Negative effect |
| | | Van der Waals forces ↓ | Negative effect |
| | Ionic strength ↑ | Competitive adsorption ↑ | Negative effect |
| | | Salting out ↑ | Positive effect |
| | pH ↑ | Dissociation ↑ | Negative effect |
| | | Polarity ↑ | Negative effect |
| | | Hydrophilicity ↑ | Negative effect |

$$K_P = \frac{C_S}{C_W} \approx \frac{S_S}{S_W} \tag{6}$$

$$K_P = \frac{C_{solvent}}{C_{water}} \approx \frac{S_{solvent}}{S_{water}} \tag{7}$$

where $K_P$ is a function (Solubility), C is the concentration(s), S is the solubility, s is solvent, and w is water. Partitioning has been widely adopted as a reliable way to model the distribution of an organic component/compound in the environment. Benson et al. (2021) studied the physisorption and chemisorption mechanisms of organic chemical contaminants' interactions with polymers typically used in plastics and their variability in sorption capacities. In general, adsorption processes depend on the type of pollutant and the polymer that may have gone through in the environment (Table 6 and Fig. 5).

## 8. Cleaner production (CP) as a sustainability key

Many countries of the world have been practicing CP for over a decade to enhance environmental sustainability (Verrier et al., 2016). The persistent rise in world industrialization has created a kind of environmental challenge that needed to be addressed promptly (Mahbub et al., 2016). As a result, the occurrence of any environmental depletion that is likely to arise in any part of the globe is capable of harming the completely predominant ecosystem while its negative effect can be experienced throughout the entire localities or regions (Severo et al., 2015). The reduction or minimization of the environmental effect of any organization can be achieved through different strategies and the adoption of sustainable environmental practices that include cleaner production strategies. The United Nations Development Program was responsible for the development of CP as a reliable tool or mechanism for executing a preventive program that was warmly accepted and put into practice in many developing countries across the globe (Severo et al., 2015). The concept of CP aimed at the continuous adoption of economic principles, environmental, and technological methodology in

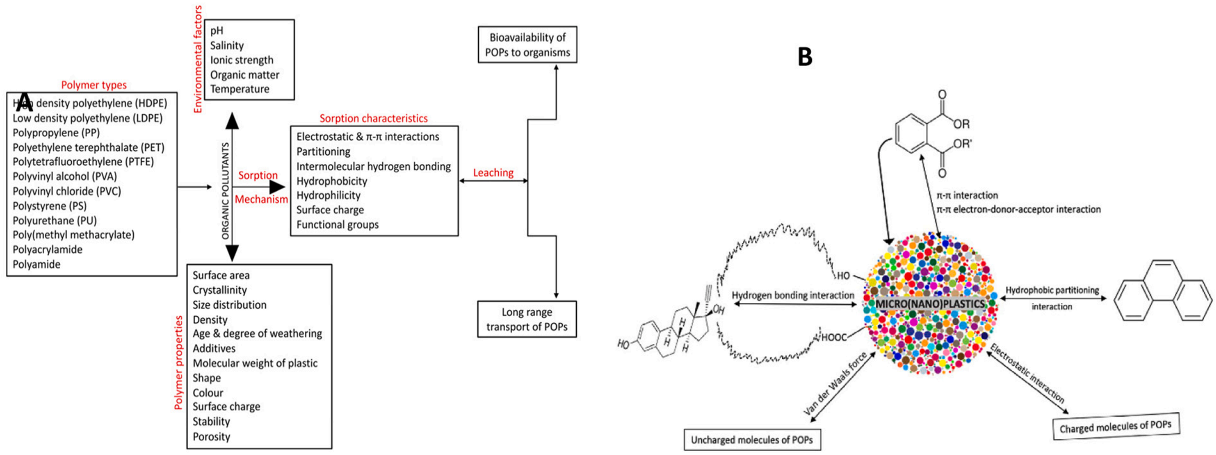


**Fig. 5.** A. Factors that govern the sorption of organic pollutants and B. Sorption mechanisms of organic contaminants to microplastics (Benson et al., 2021),

production and processes to ensure an increment in the efficiency of utilization of raw materials, water resources, cleaner bioresources, and energy by avoiding generation, ensuring minimization, and recycling of waste generated across the production lines in different sectors (Mantovani et al., 2017; UNEP, 2017). Thus, the application of CP intends to apply preventive mechanisms to relegate the effect on the ecosystems to minimal. Interestingly, several studies have shown that CP can be a reliable and significant contributor to tackle different issues peculiar to environmental sustainability challenges, thus, CP aid in enhancing productivity, quality and enable the efficient use of materials and essential resources an indication to improve their sustainability efficiency (Verrier et al., 2016; Ramos et al., 2018).

## 9. Outlook

The production of waste in the whole world has been tremendously growing and it is expected to keep growing. However, MSW has various pollutants that might have value and can be used for various purposes. The poorly managed MSW will need further research to determine its impact on the environment and human health. Furthermore, more technological investments are required to develop advanced systems for the collection of leachates as well as the emissions of toxic gases. In addition, to ensure long-term sustainability in the MSW management system, different management parties should have a solid working relationship. Improved waste collection system, increased waste collection, and disposal fees are some of the actions that can help in the management and reduction of MSW. Furthermore, it can help as well in funding the existing facilities for MSW treatment, encouraging the public to minimize the generation of the MSW, and amending the way they manage the produced waste.

## 10. Conclusion

This study for the sustainable and long-term management of MSW has accentuated that proper evaluation of landfill management coupled with probable methods need to be critically evaluated to ensure that uncompromising MSW management standards are maintained and sustained. The landfill provides cheap and simple waste disposal means, but it could be associated negative effects on the environment if not properly handled. With adequate measures, these impacts can be drastically reduced. All relevant environmental factors should be quantified to describe a particular process and understand and evaluate the dynamic behavior and principles of transport of a given pollutant in the environment.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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