Chapter

Perspective Chapter: Industrial Waste Landfills

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Abstract

Wastes are generated as a result of anthropogenic activities. The rapid industrialization of human society in the twenty-first century has led to an increase in the generation of industrial wastes that have negatively impacted humans and the environment. While industrial operations and techniques have improved globally, leading to a higher standard of living, economic prosperity, and healthcare delivery, industries have continued to produce waste on a scale never before seen. This chapter discussed industrial wastes, waste generation, and industries involved, waste disposal, landfilling as a disposal method, effects of waste disposal, modern techniques in industrial waste management, landfill sustainability, and regulations.

Keywords: industrial waste, waste generation, waste disposal, effect of disposal, waste management, landfill sustainability and regulations

1. Introduction

Industrialization, which meets the needs of a rapidly increasing global population, is the backbone of economic development and human welfare in any society. However, the proliferation of industries and industrial activities in many countries, especially developed countries in Europe and America, has led to environmental pollution and eco-deterioration around the developed world. Industries in less developed countries of Africa and the Sahel are no different as the impacts of their activities on the environment continue to produce far more deterioration due to poor pollution management and control. For instance, Teku [1] and Firdissa et al. [2] stated that in Ethiopia, rapid industrialization has led to the generation of industrial wastes including hazardous wastes, and improper management of the vast amount of these wastes is one of the most critical environmental problems in Addis Ababa. One of the main concerns of environmental engineers and activists in Nigeria, especially in the state of Lagos with a small land mass in comparison with its large population, is the ever-expanding solid waste landfills and their attendant environmental degradation caused by leachate formation (**Figure 1**), which can contaminate arable agricultural land, surface water, and aquifers [3].

Figure 1.
Leachate flowing across the road at a solid waste dumpsite in Lagos, Nigeria [3].

2. Industrial wastes and their types

Industrial wastes are unwanted and residual materials produced by industrial activities and may include any product discarded as useless during such manufacturing operations as metal deformation, metal casting, sheet metal forming, polymer processing, machining, finishing, assembly, foundry, steam generation, and coal-fire electrification, construction works, textile manufacture, pulp and paper mills, and mining operations to mention a few [4]. These wastes are basically generated in large quantities when compared to municipal wastes and mostly at every stage in the manufacture of products, which turns raw materials into finished goods that are sold or distributed [4]. Manufacturing processes commonly generate all forms of waste including gaseous, liquid, and solid wastes [4].

Industrial waste products have particularly dangerous properties such as toxicity, ignitability, corrosivity, or reactivity [5], can negatively impact human health and the environment [6] or pollute nearby soil, adjacent to water bodies or contaminate groundwater, lakes, streams, rivers, and coastal waters [3]. At a typical landfill site, industrial waste is often mixed with municipal waste, which makes accurate assessments of industrial waste produced difficult [2]. In the United States, for instance, an estimation gave more than 7.5 billion tons of industrial waste produced annually, as of 2017 [2]. Problems associated with generation of industrial waste have forced most countries and municipalities to enact legislation to deal with the situation [2]. While strictness and compliance with industrial waste pollution legislation may vary from place to place, enforcement of such legislation is often an issue [2]. The different types of industrial waste generated according to the industrial sector are shown in **Table 1** below.

2.1 Classes of industrial wastes

Industries generate various kinds of waste depending on their manufacturing processes and the finished product being produced, which are classified according

S/N	Industrial sector	Description/industrial processes	Typical type of waste
1.	Mining and quarrying	Extraction, beneficiation, and processing of minerals	Tailings, phosphogypsum, muds, solid rock, and slag
2.	Energy	Electricity, gas, steam, and air conditioning supply	Boiler slag, fly ash, bottom ash, sludge, particulates, and used oils
3.	Manufacturing	Chemical Food Textile Paper	Sludge, spent catalyst, chemical solvents, reactive waste, alkali, used oils, ash, and particulate waste Packaging, carton, and plastic Pigments, peroxide, textile wastes, alkali, organic stabilizer, chemical solvents, heavy metals, and sludge Chemical solvents, sludge, wood waste, and alkali
4.	Construction	Demolition and construction activities	Glass, plaster, cinder blocks, concrete, mansory, gypsum, wood shingles, asphalt, metals, and slate
5.	Wastewater services	Water supply, collection, and treatment	Spent sludge and adsorbents

Table 1.
Type of industrial waste according to industry sector [7].

to their state/nature, degradation potential and toxicology, and hydrocarbon content [8]. Generally speaking, industrial waste can be classified as biodegradable and non-biodegradable wastes. The different classes and more specifically, types of industrial wastes generated during any manufacturing process are described in the following section.

2.1.1 Biodegradable and nonbiodegradable industrial wastes

Industries generate wastes that may or may not be decomposed by microorganisms (such as bacteria, fungi, algae, protozoa) when deposited in landfills.

2.1.1.1 Biodegradable industrial wastes

Biodegradable industrial wastes are produced from industrial processes, which generate decomposable material in which decomposition is caused by microbial activities and the material is then converted to gas and water. These kinds of industrial wastes are similar to municipal wastes and are usually generated by food processing and agro-allied industries, slaughterhouses and dairy industries, etc. [8]. These wastes are nonhazardous, do not require special kind of treatment, and are mostly solid. They include such wastes as animal bones, fur, wheat, animal skin, leather, wool, discarded fruits, and so on [8].

2.1.1.2 Nonbiodegradable industrial wastes

These are industrial wastes that cannot be decomposed into gases and water. They are generated by industries such as fertilizer, chemical and petroleum, drugs and pharmaceutical, mechanical, dye industries, nuclear power plants, polymer processing, construction, foundry, metal, and steel plants [8]. Examples of this waste are polyethylene terephthalate (PET) plastics, fly ash, synthetic fibers, glass, gypsum, and radioactive wastes [8]. Most landfills consist of nonbiodegradable industrial waste due to their nondecomposing nature [8]. Other types of industrial wastes can further be divided into the following types based on their nature.

2.2 Types of industrial wastes based on their nature

2.2.1 Industrial solid waste

Industrial solid waste (**Figure 2**) is produced by specific manufacturing processes and can either be biodegradable or be nonbiodegradable but mostly, it is neither municipal nor hazardous wastes [8]. It encompasses a wide range of materials of varying environmental toxicity [8]. Typically, this range of waste materials would include paper, packaging materials, waste from food processing and agrochemical, oils, solvents, resins, paints and sludges, glass, ceramics, stones, metals, plastics, rubber, leather, wood, cloth, straw, abrasives, etc. [8]. Generally, according to Ref. [5] there are about 43 different industrial solid waste material ranges that can be categorized into 5 groups, which include the following:

- Solid chemicals.
- Drugs and food.
- Textile and apparel including clothes, leather, and laundry.
- Energy such as coal processing, power plants including thermal and nuclear.
- Pulp and paper, steel, rubber.

The major generators of industrial solid wastes are the thermal power plants producing coal ash, integrated iron and steel mills producing blast furnace slag and steel melting slag, nonferrous industries like aluminum, zinc, and copper producing red mud and tailings, sugar industries generating press mud, pulp, and paper industries producing lime and fertilizer and allied industries producing gypsum, and food and pharmaceutical industries producing solid food and biomedical wastes, respectively [9]. It is important to note that there is a distinction between solid and liquid industrial wastes because they are handled very differently and are generated on largely different scales [9].

2.2.2 Industrial hazardous waste

The term industrial hazardous waste refers to any semisolid, solid, sludge, or liquid waste generated from such industry activities as mining, medical services, and public services including waste incineration plants, waste recycling plants, which contains chemicals, pathogens, radiation, heavy metals, or other toxins thereby posing a significant threat to human health and the environment [10]. Hazardous waste generated in industries may be listed or characteristic (**Figure 3**). While listed industrial hazardous wastes are produced by specific industries or generated from common manufacturing processes and discarded as waste commercial products, characteristic

Figure 2.
A stack of waste paper produced in the pulp and paper industry [7].

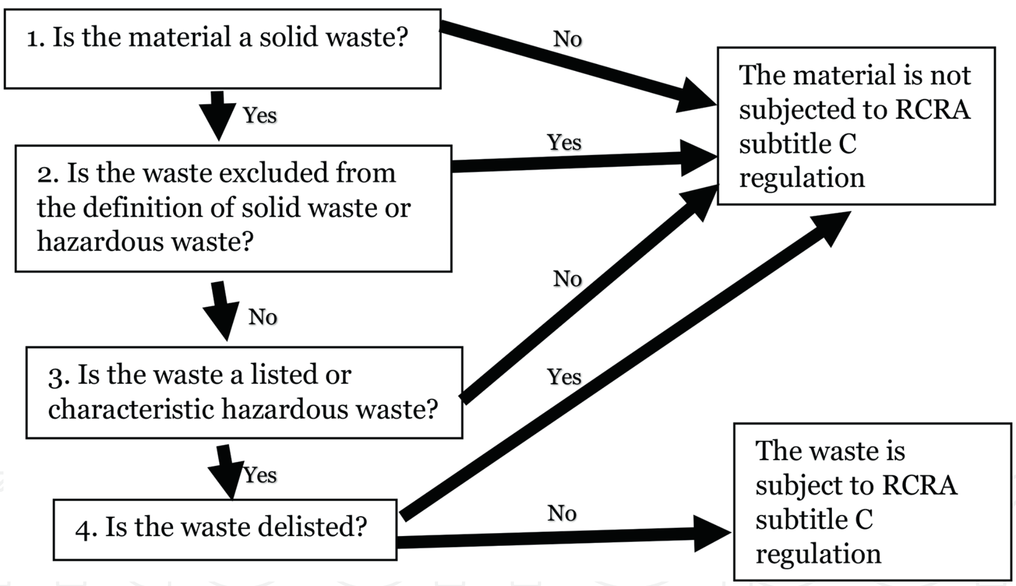

Figure 3.
Identification of industrial hazardous wastes [11].

industrial hazardous wastes show one or more characteristic properties such as ignitability, corrosivity, reactivity, or toxicity; some hazardous wastes are referred to as mixed wastes when they contain both hazardous and radioactive components [11]. All forms of hazardous wastes including listed, characteristic, and mixed are regulated under both Resource Conservation and Recovery Act (RCRA) of 1976 and Atomic Energy Act (AEA) of 1946 [12].

Common examples of hazardous wastes are chlorinated aliphatic hydrocarbons, multisource leachate, petroleum refinery sludge, explosive solvent, inorganic pigment, organic and inorganic chemicals (listed wastes), flammable fluids, aqueous acids and bases, explosive and toxic gases (characteristic wastes), low-level mixed waste (LLMW), high-level mixed waste (HLW), and transuranic waste (MTRU) (mixed wastes) [11].

Nonhazardous industrial wastes may be generated from industrial activities associated with the production of iron and steel, pulp and paper, glass, electric power generation, electronic and electrical products, construction and concrete, and they do not meet Environmental Protection Agency's (EPA) definition of hazardous waste [12]. Although they are not considered to pose immediate risks to human health, they can still be harmful to the environment as a result of methane emission during decomposition [12]. Some common industrial nonhazardous waste is ash, sludge, antifreeze, grinding dust, etc. Electronic wastes (or E-wastes) are generally nonhazardous; however, there are a few that may be considered hazardous. Electronic devices and components that can be disposed of as nonhazardous include zinc plating, aluminum, copper, gold, etc. [12].

2.2.3 Industrial chemical waste

These are solid, liquid, or gaseous materials that are hazardous in nature and are in excess, unused, or unwanted during the manufacture of a commercial product. Chemical wastes in the industry may result from expired or extraneous materials when certain industrial processes or products have become extinct [13]. Also, materials that are contaminated with flammable liquids such as acetone, acetonitrile; leachate toxic substances like heavy metals, pesticides; corrosive substances like potassium hydroxide pellets and hydrochloric acids; reactive substances like cyanides, oxidizers, sulfides, explosives, benzoyl peroxide, and toxic substances like mutagenic, carcinogenic, chloroform, ethidium bromide; other chemical wastes are pyritic slag, acidic slag, alkali slag, salt mud, mud from chemical production kettle, residues of refining or distillation; all these require careful handling and disposal [13].

2.2.4 Industrial radioactive waste

Radioactive or nuclear wastes are generated by industrial activities that use or produce radioactive materials. These wastes are hazardous as they emit radioactive particles, which are risky and can pose huge threat to the environment if not properly handled [14]. Radioactive wastes can arise from the commercial operations of nuclear reactors, hospitals, research facilities, and fuel processing plants [14]. Examples of radioactive wastes are low-level wastes, which include common everyday materials such as rags, plastic bags, paper, and packaging materials; high-level wastes such as used fuel from nuclear reactors and wastes from reprocessing of used-up nuclear fuel; transuranic wastes and uranium or thorium mill tailings [14].

3. Industrial waste generation

Industrial wastes are unavoidably produced during manufacturing process of commercial products by different industrial activities from agriculture to extraction of natural resources. The type of waste generated and its characteristic depend on the industry sector [15] and the inherent industrial process employed to produce finished products in such industry. Generally, according to Ref. [16] the world currently generates about 2.02 billion tons of solid waste annually; this figure is projected to be on steady increase (**Figure 4**) and may reach 3.40 billion tons by 2050.

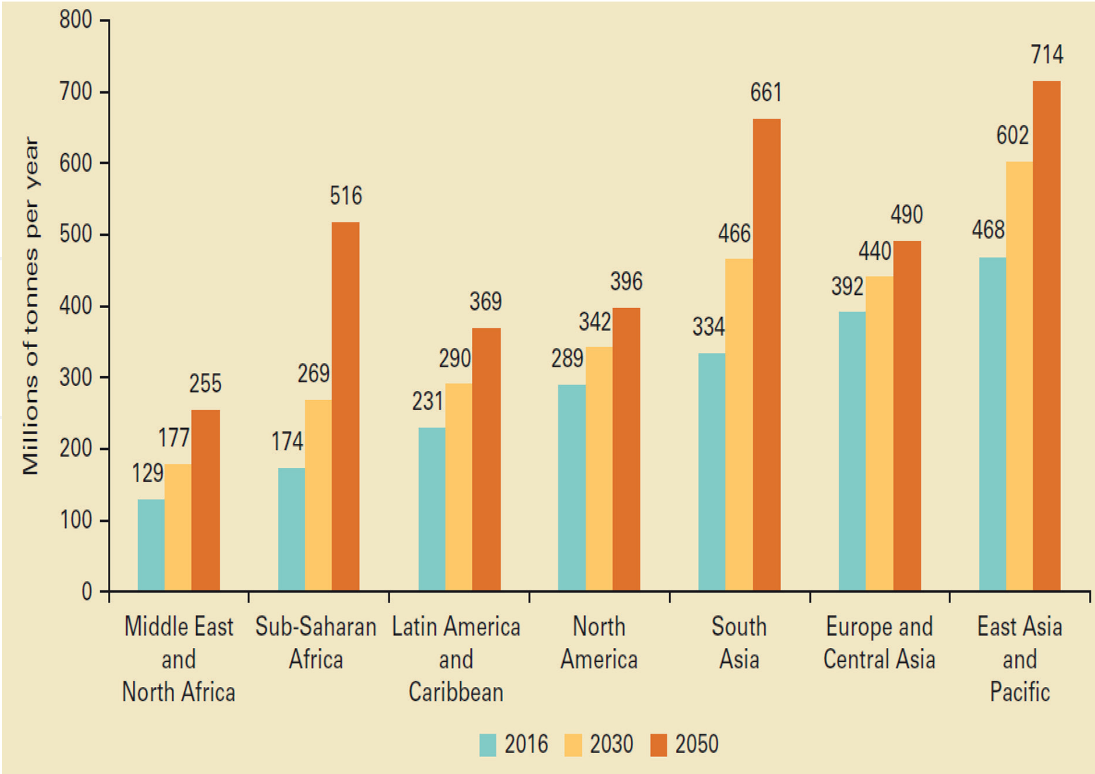

Figure 4.
Projected global waste generation by region (million tons/year) [16].

The volume of waste generated in industries around the world has equally been on the rise over a long period of time. In the United States for instance, the amount of hazardous waste produced by industries has increased from about 4.6 million tons annually after World War II, to an estimated 57 million tons by 1975 [17]. By the 1990s, the volume of waste produced by American industries had increased to approximately 260 million tons [15]. **Table 2** shows the amount of waste in million tons generated in industries in different regions of the world in 2011.

Solid wastes from industries are generated by construction activities, cement and limestone production, mining and mineral extraction, steel and iron ore

S/N	ITEMS	EUROPE	AMERICAS	AFRICA and MIDDLE EAST	ASIA PACIFIC	GLOBAL
1	Industrial wastes generated (Million tons)	1933	915	921	5357	9126
3	Countries	Germany, United Kingdom, France, Russia, and Bulgaria	United States, Brazil, Canada, Chile, and Columbia	South Africa, Saudi Arabia, United Arab Emirates, Egypt and Tunisia	China, Japan, India, South Korea, and Australia	

Table 2.
Volume of industrial wastes generated in different regions of the world in 2011 [18].

S/N	Type of industrial solid waste	Amount produced (million tons)	Product manufacturing process/waste production source
1.	Steel and blast furnace residue	35.0	Conversion of pig iron to steel and in manufacturing of iron rod
2.	Brine mud	0.02	Caustic soda production
3.	Copper slag	0.0164	By-product of copper smelting
4.	Fly ash	70.0	From coal-based thermal power plants
5.	Kiln dust	1.6	From cement production plants
6.	Lime sludge	3.0	In sugar, paper, fertilizer, soda ash, calcium carbide, production, and tannery industry
7.	Mica scrap waste	0.05	In mica mining.
8.	Phosphogypsum	4.5	In phosphoric acid and ammonium phosphate production
9.	Red mud or bauxite	3.0	In mining and extraction of aluminum from bauxite
10.	Coal washery dust	3.0	From coal mines
11.	Iron tailings	11.25	In production of iron ore
12.	Limestone waste	50.0	In limestone production/quarry

Table 3.
Industrial solid waste generated from typical industrial manufacturing processes [9].

production, and solid chemical production as can be seen in **Table 3**, which shows industrial solid wastes produced from typical manufacturing processes [9]. From a global standpoint, plastic wastes account for the most type of solid waste generated

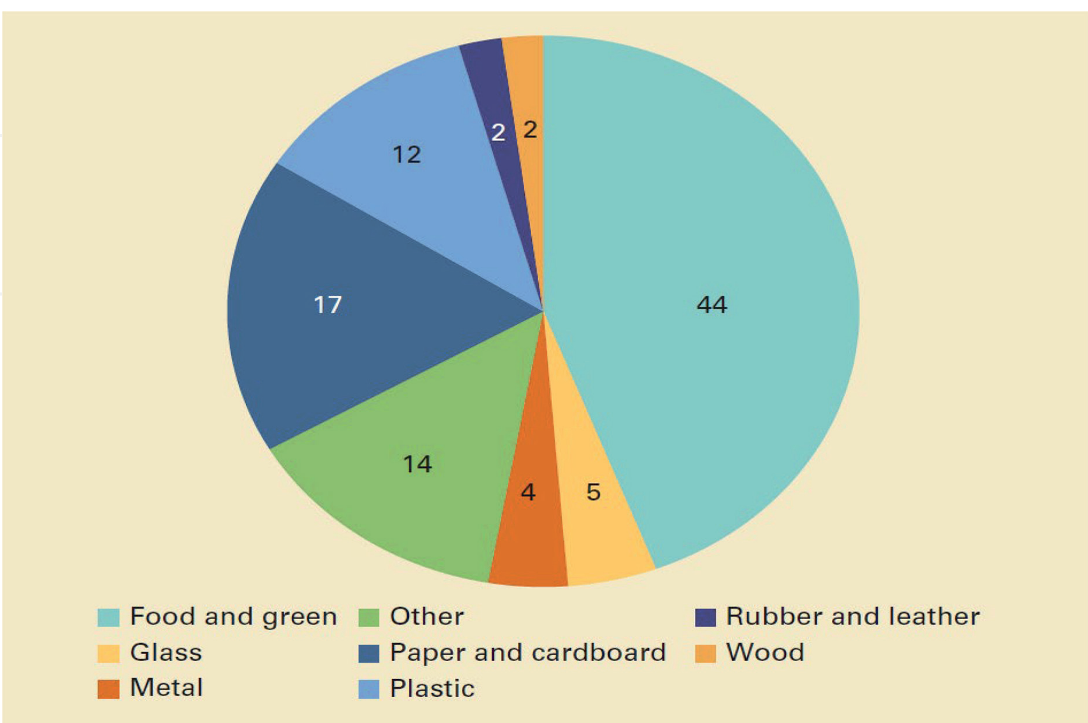

Figure 5.
Global composition of solid waste generated annually (percent) [16].

S/N	MANUFACTURED PRODUCTS	ASSOCIATED HAZARDOUS WASTE
1	Pesticides	Organic chlorine and phosphate compounds
2	Textiles	Heavy metals, dyes, organic chlorine compounds, and solvents
3	Medicines and drugs	Organic solvents and residues, heavy metals such as mercury and zinc
4	Leather	Heavy metals, organic solvents
5	Oil, Petroleum products	Oil, phenols, organic compounds, heavy metals, etc.
6	Metals	Heavy metals, fluorides, cyanides, acid and alkaline cleaners, solvents, and pigments.
7	Paints	Heavy metals, pigment, solvent, and organic residues

Table 4.
Industrial hazardous wastes associated with the production of certain commercial products [19].

(**Figure 5**) by both industry and household annually [16]. Industrial hazardous wastes, on the other hand, can be generated by industries manufacturing pharmaceuticals and drugs, paint, textile, pesticides and agrochemicals, plastic and polymer, tannery, and petroleum and petrochemical industries [17]. In **Table 4**, typical hazardous wastes generated from the manufacture of commercial, finished products are presented.

Chemical wastes from industries are generated by industrial processes, which produce chemicals such as toluene, acetone, benzene, urea, potash, sulfuric and hydrochloric acids, utilized in different sectors such as agriculture, military, service

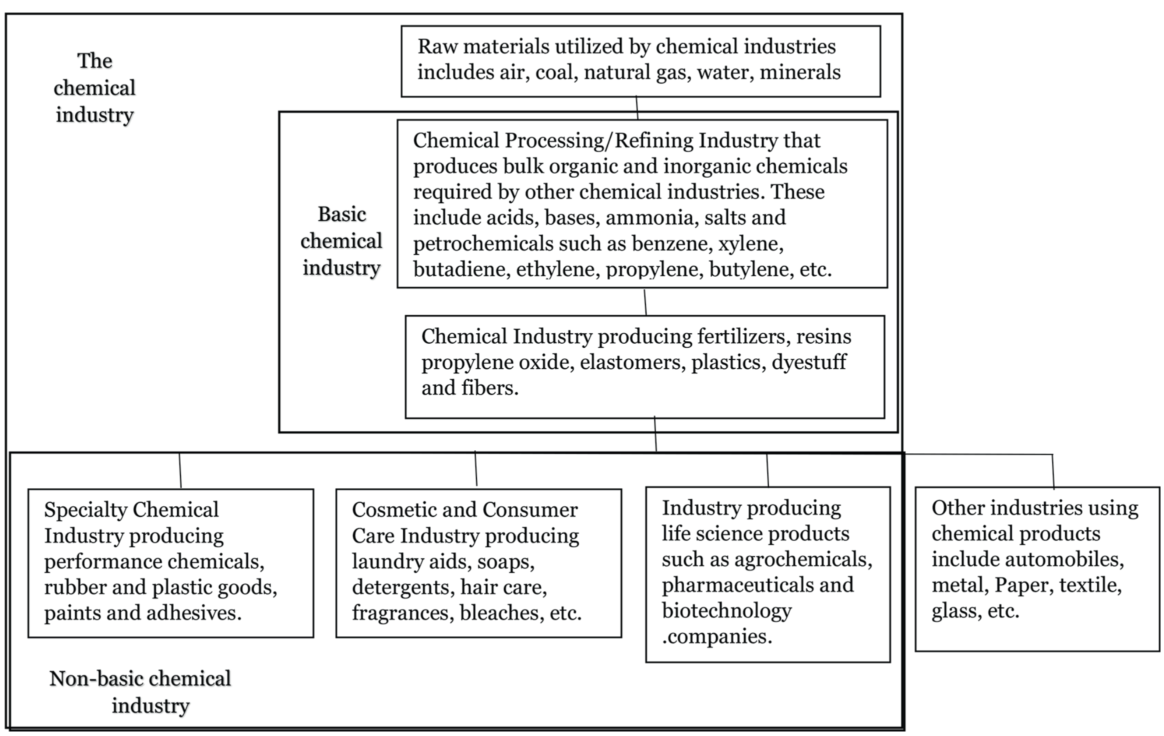

Figure 6.
The different chemical industries that produce industrial chemical waste [19].

S/N	Radioactive waste	Industrial process/source of waste	Associated radiation/half-life (years)
1.	Very low-level waste	Medical procedures	^{131}I/8.028 days
2.	Low-level waste	Industrial waste from nuclear power plants; medical and research wastes such as paper, plastic, and glass	^{3}H/2.32 ^{60}Co/5.27
3.	High-level radioactive waste	Used fuel from nuclear power reactors; liquid waste from the reprocessing of spent fuel	^{90}Sr/29.78 ^{137}Cs/30.07
4.	Mixed waste	Weapon production waste and some research wastes	^{239}Pu/24,100 ^{241}Pu/14.4
5.	Transuranic waste	Weapon production waste and mixed transuranic waste	^{238}Pu/87.7 ^{241}Am/432.7
6.	Naturally occurring radioactive material (NORM) wastes	Crude transport; scale buildup on pipe walls carrying petroleum products	^{226}Ra/1599 ^{228}Ra/5.76
7.	Uranium or thorium mill tailings waste	Milling for rare earth metal extraction	^{230}Th/75,400

Table 5.
Industrial radioactive wastes produced from various sources and processes [21].

industry, construction, consumer goods manufacture, and cosmetics [13]. Chemical wastes are also produced by paint industries and textile industries [20]. A block diagram of the general overview of the chemical industry is presented in **Figure 6** below.

Industrial radioactive waste is produced by such industries as nuclear power generation, mining, military and defense, medicine, and research institutes [14]. **Table 5** shows the various industrial radioactive wastes generated by different industrial operations.

4. Industrial waste disposal and landfilling

The millions of tons of waste generated by manufacturing industries are collected, removed, and disposed of to prevent pollution and ensure environmental protection [9]. However, disposal is only carried out after applying waste reuse and waste recycling management techniques. Other reasons for waste disposal in industries are as follows: to generate revenue from waste and to create employment opportunities [9]. Since waste has different characteristics, the method of disposal varies from one waste to another. When industrial waste is generated, pre-disposal activity like segregation is often carried out to separate waste according to type and nature. A lot of wastes are a mixture of hazardous and nonhazardous wastes and their contents may even be liquid [9]. By segregating toxic constituents in wastes, isolating liquid fractions, and keeping hazardous streams away from nonhazardous wastes, industries can save substantial amounts of money on disposal or get new opportunities in waste recycling and reuse [9]. Major waste disposal methods are described in the following section.

4.1 Industrial waste disposal methods

Industrial waste disposal can be carried out by methods such as waste recycling, waste composting, waste incineration, and landfilling.

4.1.1 Recycling of industrial waste

Waste recycling, also called beneficial waste usage, involves reusing waste materials generated from industrial processes to produce same or completely different finished products [22]. This has the advantage of reducing the need for producing too many new items and, in turn, reduces disposal at landfills which ultimately is beneficial to the environment [23]. There are a lot of opportunities for waste recycling in the industry and some wastes produced can be reused for road construction and repair, bridge construction, production of consumer goods, etc. [22]. Common recyclable industrial solid waste materials are coal combustion products, demolition and construction materials (**Figure 7**), scrap tires, and foundry sand [22]. Some of the reasons for recycling wastes by any industry are as follows: to reduce carbon footprint and conserve resources, to earn and save money, to save resources and energy when recycling machines are used, to reduce overall disposal cost, to improve company's reputation and create job opportunities and to build brand as ecofriendly, etc.

4.1.2 Industrial waste composting

Industrial waste composting or commercial composting is a large-scale recycling of organic, biodegradable waste materials in order to produce natural soil enhancers or fertilizers used in farming [24]. The composts formed in this waste disposal method (the process is shown in **Figure 8**) are then sold to agricultural centers, farms, or plant nurseries. Typically composting industrial wastes is achieved by first, collecting waste from food processing industries, grocery stores, large restaurants, and other commercial facilities and processing them at a compost processing plant (compost machine) where foreign materials are initially removed and the food wastes mixed with sludge [24].

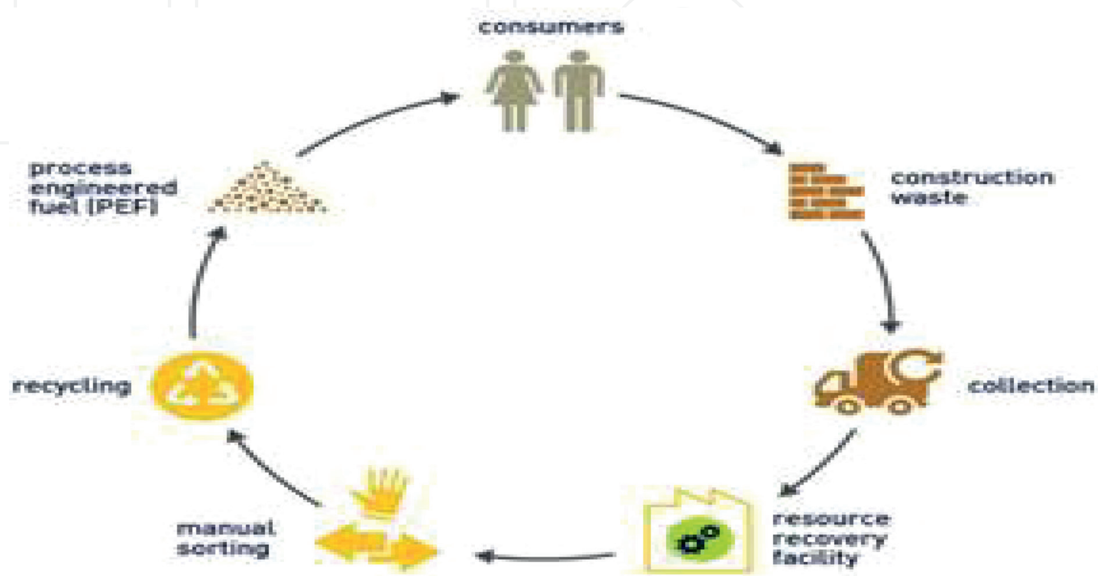

Figure 7.
Industrial construction waste recycling [23].

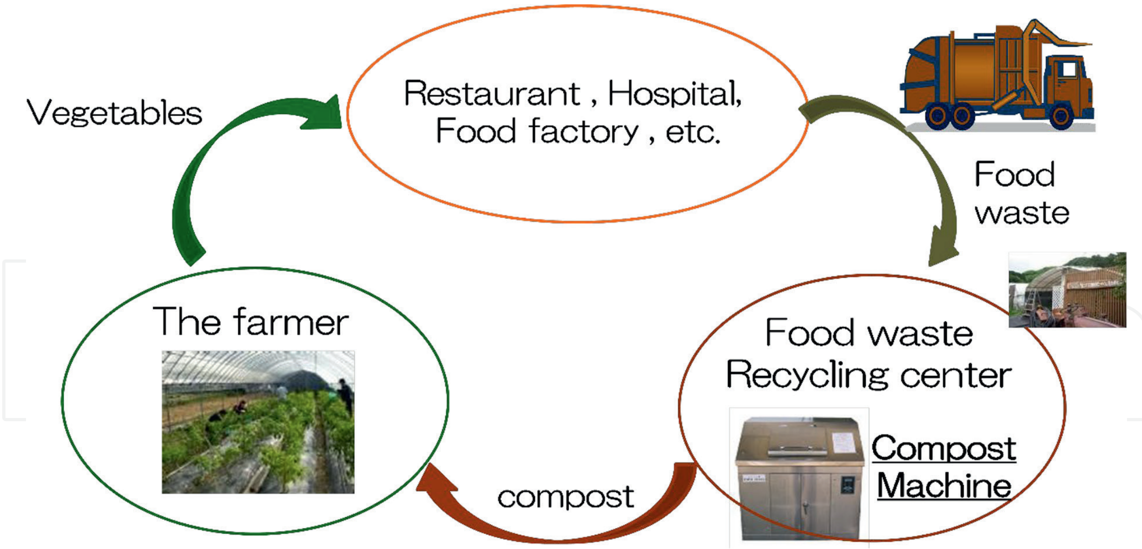

Figure 8.
Food waste recycling/compost production process [25].

4.1.3 Industrial waste incineration

Incineration of wastes from industries (**Figure 9**) is a disposal technique that involves burning combustible materials in wastes thereby converting them to flue gas (stack gas) and ash and producing heat energy that can be utilized for power generation [27]. Industrial waste incineration is a thermal waste disposal method and can be regarded as a waste-to-energy technology. The purpose of this waste disposal technique is to reduce waste volume and save landfilling costs, to prevent the release of chemical and toxic substances to the environment, and to generate revenue from energy recovered from waste combustion, which can be used for heating or electricity generation [27]. Incineration is ideal for disposing of industrial wastes from the medical, food processing, chemical, and nuclear power sectors where high temperatures are used to destroy pathogens, toxins, and hazardous materials from waste generated in these sectors [28]. There are, however, growing concerns about the environmental

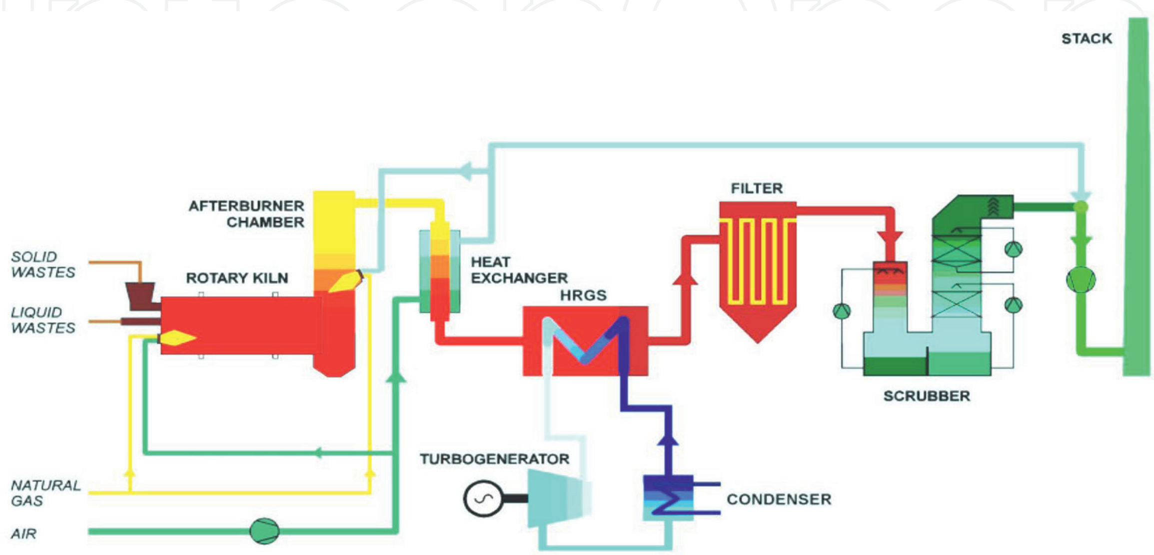

Figure 9.
Industrial waste incineration process [26].

effects of burning industrial wastes in incinerators due to the release of toxic gases during combustion.

4.1.4 Landfilling and industrial waste landfills

Landfilling is the most common, globally practiced solid waste disposal technique that involves storing large metric tons of waste in an excavated space. Landfills can store municipal, industrial, green, or hazardous wastes. According to Ref. [29] in a 2010 study, landfilling is responsible for over 30% of waste disposed of or managed in the European Union. The researchers noted that all the countries of the European Union generated about 550 kg of municipal solid waste per household in 2010 and over 400 kg of such waste was managed per person out of which almost 40% was landfilled and lesser percentage incinerated, recycled, or composted. Landfilling is practiced due to its advantages that include large volume storage, inexpensive operational procedures, and maintenance cost when compared to a disposal method such as incineration [29] but it has also been observed to pose huge environmental risks and endangerment as a result of the formation of biogas produced by the fermentation of organic matter in decomposing solid waste and leachate formed by the percolation of water through waste [3].

It is important to distinguish between an engineering landfill, whose main purpose is to ensure safety by reducing harm from accumulated wastes and allowing safe decomposition [30] and an open dumpsite (**Figure 10**). Landfills are setup and controlled by the municipal, state, or federal governments and as such are built at designated places while dumpsites on the other hand are dug by individuals, households, or communities without special consideration for setup site [30]. Landfills are covered with compact soil on regular basis to prevent offensive odors (due to biogas formation) from polluting the surrounding area; dumpsites are usually not covered with soil and so, cause air pollution [30]. Also, monitoring is an important part of any

Figure 10.
A typical open dumpsite in Lagos, Nigeria [3].

landfill operation as the drainage system and the liners are monitored by engineers to ensure no seepage of polluted liquid (leachate) formed within the landfill, and enters underground water; landfills are also designed with gas collection system and treatment plants for the liquid and gas produced; dumpsites, however, do not have liners or require monitoring and they are not setup with the treatment plants [30].

There are four different types of landfills that can be used for waste disposal. They include municipal solid waste, construction and demolition debris (C&DD) waste, hazardous waste (secure landfill), and green waste landfills [31]. The most common of the four types is the municipal solid waste landfill. This landfill is used to dispose of wastes from households and residential areas such as used tissues and waste cardboard. They have strict regulations with regard to disposal and operations, groundwater monitoring, landfill lining, closing practices, etc. [31]. The C&DD landfill is an industrial waste landfill used for disposing of majorly construction or demolition solid waste debris such as concrete and bricks. They may also be used to dispose other types of industrial solid waste such as asphalt, gypsum, metals, lumbers. C&DD landfills are used as material recovery facilities where wastes are sorted according to their usefulness and reusable wastes are separated from nonreusable ones [31]. Hazardous waste landfills are the most structured and regulated of all the landfill types, and this is due to the characteristic of waste disposed here. They may also be regarded as industrial waste landfill as they can be used to dispose industrial hazardous wastes such as pelletized potassium hydroxide, cyanides, oxidizers, sulfides, ethidium bromide. They store hazardous wastes in such a way as to prevent accidental discharge into the environment [31]. Lastly, green waste landfills are storage areas for organic waste materials to decompose naturally into compost. They are used to dispose biodegradable waste such as food, fruits, vegetables, garden, and other agricultural wastes [31]. A global comparison (**Figure 11**) of all the solid waste management techniques discussed above showed that the open dumpsite is readily utilized for disposal of waste. This can be attributed to the fact that dumpsites are setup any and everywhere regarded for proper site selection [16].

4.1.4.1 Industrial waste landfills

The large volume of wastes generated from manufacturing processes, especially solid wastes, are disposed at an industrial landfill. Although separate industrial landfills can be used to dispose construction, demolition wastes (C&DD landfill), and hazardous wastes, in practice, these landfills are combined in one facility as industrial waste landfill. Because of the nature of industrial wastes, landfills are designed with all the qualities and characteristics of engineering, sanitary landfill with modern design, stricter regulations, and mode of operations. Some of the design requirements of an industrial waste landfill involve provision of a compacter or compressor and plastic covering for top wastes after each operation, using an impervious double liner at landfill bottom [32], gas and leachate collection systems, groundwater quality monitoring system, etc. [33].

4.1.4.2 Industrial waste landfill design structure

One of the major activities carried out before the design of any engineering landfill is site selection. Important consideration must be given to the location of the facility to reduce operational impact on immediate surrounding and environs. Usually, tests are carried out to determine such factors as surface water vicinity, groundwater

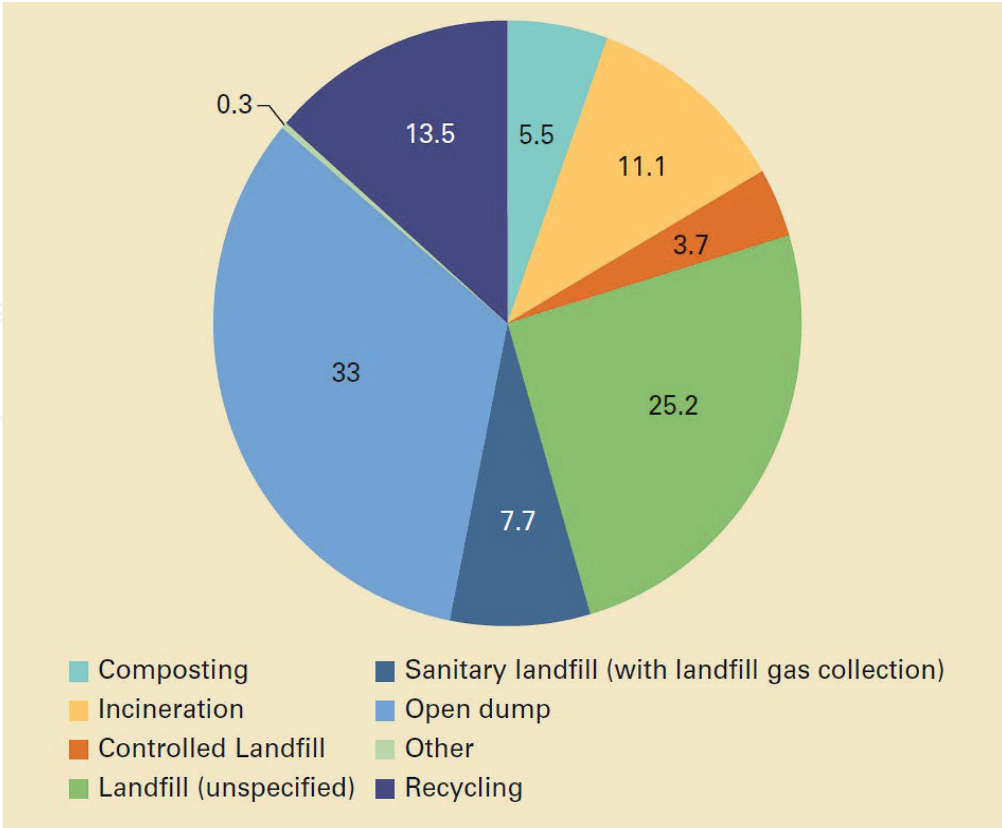

Figure 11.
Global comparison of solid waste management techniques (percent) [16].

depth, land slope, soil permeability, land elevation, soil stability, stratification and lithology faults, flood susceptibility, type of land use, urbanization and land settlement, cultural and protected site, road, airport and railway proximity, wind direction, pipe- and powerlines proximity [34]. The general layout of the landfill facility according to [9] should be made to comprise the following units as a minimum:

- Operational building with amenities.
- Operational area.
- Vehicle and instrument workshop.
- Control systems.
- Illumination, roads, fencing, trenches, etc.
- Truck/vehicle weighbridge.
- Laboratory for sample analysis.

The engineering design involved in the construction of an industrial waste landfill requires constructing layers of different sizes in a known volume of excavated space (**Figure 12**). The smallest layer is usually located at the bottom of the landfill, while the largest layer is at the top: to prevent collapse of the surrounding area and indeed, the landfill [31]. These layers facilitate decomposition of waste materials and

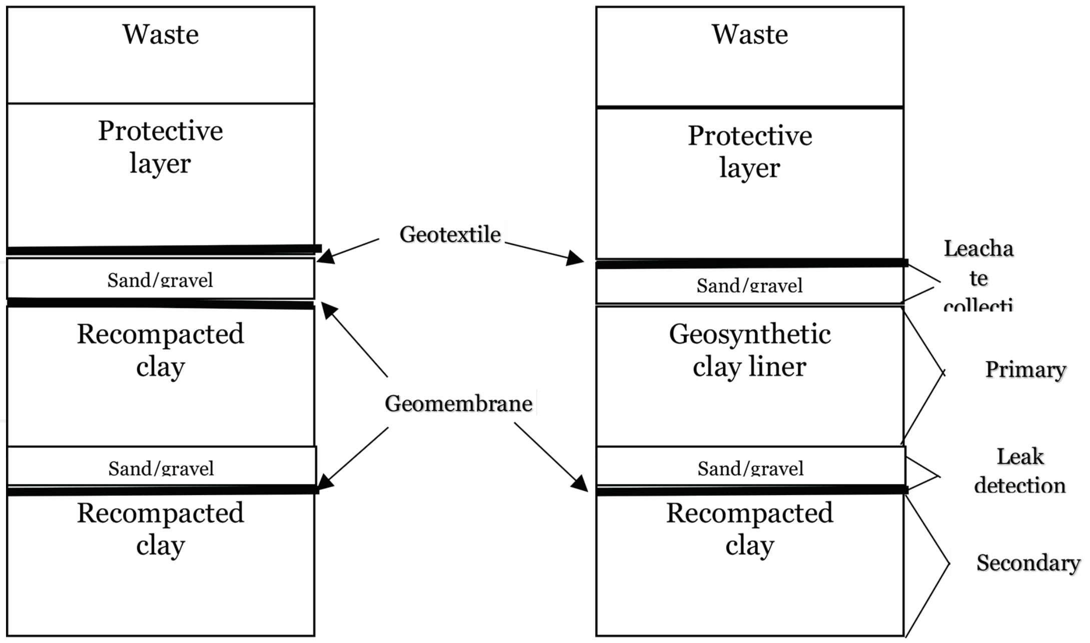

Figure 12.
Schematic representation of a typical industrial waste landfill structure [35].

entrapment of toxic gases released from within the landfill [31]. The different layers of an industrial waste landfill are described below.

4.1.4.2.1 First or bottom layer

This is the liner system. Industrial waste landfills are mostly designed with double-liner systems especially when they dispose hazardous waste (**Figure 13**), although some are built with a single-liner system (**Figure 14**); these are ideal for disposing C&DD wastes. The liner system acts as a barrier that isolates landfill contents from contact with the environment thereby preventing pollution. Common liner materials include clay, geomembranes, or flexible membrane liners (FML) made from plastic materials such as polyvinyl chloride (PVC) and high-density polyethylene (HDPE),

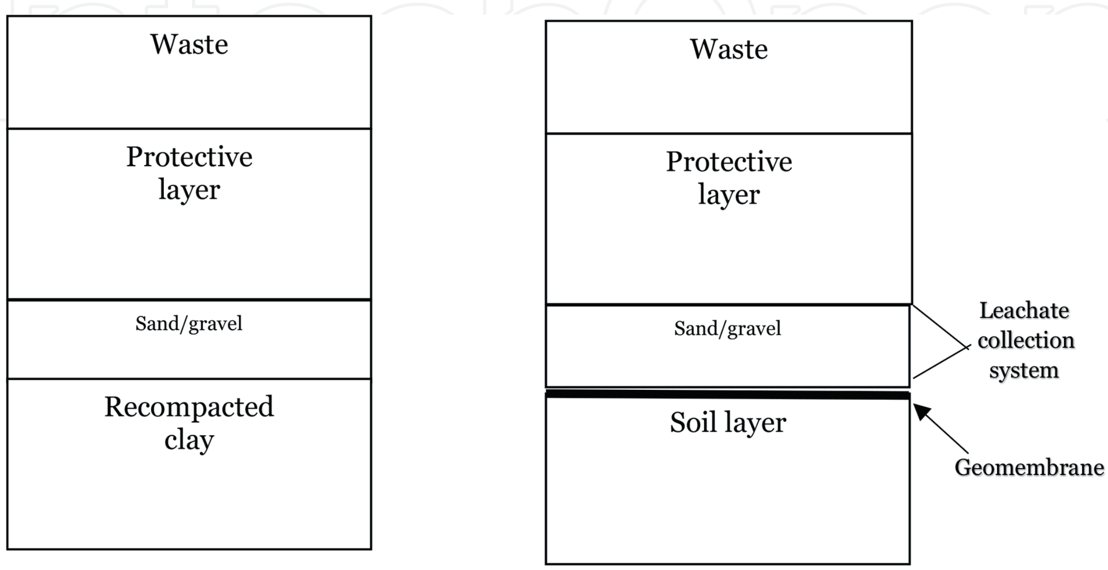

Figure 13.
Block diagram of a double-liner system mostly used in hazardous waste landfills [33].

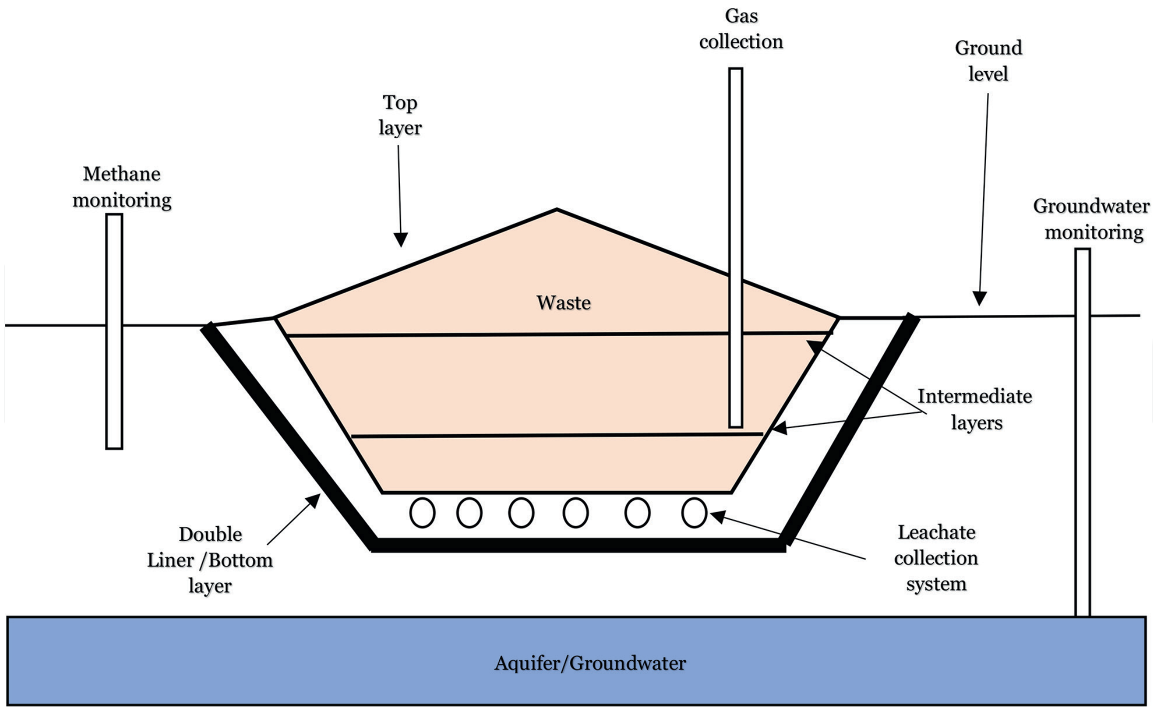

Figure 14.
Single-liner system used in C&DD and industrial solid waste landfills [33].

geotextiles, geosynthetic clay liners (GCL), and geonets [33]. The liner material is applied at the bottom of landfill to prevent seepage of liquids. Sometimes when clay is used as liner, HDPE can be applied on top of the clay as reinforcement [31].

4.1.4.2.2 Second layer

This is the drainage system. The drainage system controls toxic liquid or leachate produced from decomposing waste materials combined with rainwater runoff or snow in the landfill. The drainage layer helps in draining leachate to avoid contact with the liner system, which may be corroded by the toxicity level of leachate [31]. Leachate should never seep past the liner layer because of contamination of groundwater and soil. In order to reduce the risk of contamination, the landfill is designed with perforated pipes on top of the liners to collect all leachates at the bottom from where it is channeled to leachate treatment plant, where it is treated and then reused [31]. Stormwater and snow which may not have mixed with decomposing matter and had seeped from the top surface into the landfill are also drained away in the drainage layer.

4.1.4.2.3 Third layer

This is the gas collection system. Just as toxic liquids are produced in landfill, toxic gases (usual biogas) are also released through natural decomposition processes [31]. Methane that is a major constituent of biogas is produced in landfills. Since methane is toxic and known to contribute to global warming, it is prevented from being released into the atmosphere where it causes public health damage, by the landfill design [31]. The design of the landfill is such that gas extraction pipes are fitted into the gas collection system, which entraps methane and transports it to the gas treatment plant for electricity and power generation [31].

4.1.4.2.4 Fourth layer

This is the topmost and largest layer of the landfill that contains the disposed waste itself. A compressor is used to reduce the size of waste disposed on daily basis to avoid occupying too much space [31]. Also, compact soil is applied on top of the compressed waste to keep away windblown debris, offensive odors produced within the landfill, and pests [31].

5. Landfill sustainability

Over time, preventing, recycling, or re-using wastes have not been found to take away the need for a landfill in any waste management system as not all wastes can be recycled or recovered under all circumstances [32]. Oftentimes, the quantity of wastes to be disposed far exceeds the capacity for recovery, recycling, or incineration making the need for landfills even more inevitable, as they (landfills) have been used to dispose large quantity of wastes [32]. All of these indicate that in a typical recycling and recovery waste management practice, landfilling is a "go-to" method of waste management [32]. In landfill designs, impermeable liners are the standard for preventing environmental pollution [32]. Liners may stay intact for a long period, up to 50 or even 100 years but eventually, they will fail; this necessitates the need for landfill aftercare, which may not be sustainable [32]. Landfills should, therefore, be managed and operated so that future generations do not have to worry about their adverse effect on the environment; they should be managed in a sustainable way.

A sustainable landfill is one which attains stable conditions within a short period of time and reaches a state where the undisturbed contents no longer pose environmental risk to human health and the environment [32]. At this stage, the landfill is said to be in a state of completion and aftercare can be discontinued [32]. In sustainable landfills, waste materials are safely absorbed into the surrounding environment, whether or not they have been treated and landfill gases (LFGs) are controlled so as to minimize environmental impact [32]. In order to achieve landfill completion, waste pretreatment or bioreactor operations can be carried out in the landfill facility. Common chemicals used for pretreatment include aluminum sulfate, ferrous sulfate, ferric chloride, and ferric chlorosulfate [3]. Bioreactor operations are employed for waste treatment in a landfill [33]. A landfill bioreactor facilitates the degradation of waste by microbial activity, which may be achieved by controlling parameters such as moisture, oxygen, nutrients, pH, and temperature [33]. Since water limits microbial activity in a landfill, leachate recirculation can be used to create landfill bioreactor [33]. Recirculation increases the moisture content of the waste in the landfill thereby promoting waste degradation. Landfill sustainability can be measured (**Figure 13**) in terms of environmental, economic, and social impacts of the landfill on host community [33].

6. Environmental effect of poor disposal of industrial waste

Improper or poor waste disposal is injurious to man and the environment. Indiscriminate disposal allows for uncontrolled and unhygienic decomposition of organic, toxic, and hazardous waste materials [32]. When wastes decompose uncontrollably outside an engineering landfill facility, air pollution, microorganisms and pests infestation, and bad esthetics are the result [36]. Industrial solid wastes contain toxic and hazardous chemicals whose concentrations usually exceed permissible levels [9] and when released into the environment, these chemicals may result in physical, biological, and chemical disruptions of the ecosystem and soil fertility [36]. Plastic wastes, for instance, have been linked to endocrine disruptions in humans and animals due to the slow release of bisphenol A at disposal [37]. Toxic chemicals and other harmful substances in leachate from dumpsites or poorly managed landfills may seep into the soil and pollute groundwater [3]. Also, some industrial hazardous and radioactive wastes mixed with municipal solid wastes (cardboard and scraps) at dumpsites produce noxious gases and dioxins when burned [36]. These gases are carcinogenic and have the potential to cause disease and eventually, death from exposure [36].

Effects of improper disposal of industrial wastes on humans and animals cannot be felt without a pathway (route) for contact or exposure. Some of the exposure routes include: (i) exposure by skin contact, which is the direct contact of humans with dioxins that can bring about irritation [9]. Pollutants like corrosive acids can destroy the skin by a single, one-time exposure, while others such as organic solvents may cause damage by repeated exposure [9]; (ii) exposure by inhalation is the easiest source of occupational workplace contact with pollutants and the most difficult to control [9]. Air pollutants can affect the respiratory tract, causing damage to the lungs, bronchi/bronchioles, larynx, and trachea [9]; (iii) exposure by ingestion may cause damage resulting from absorbing or swallowing food and water contaminated by pollutants [9]. Typical effects of poor industrial waste disposal are described in the following section.

6.1 Effect on the environment

Poor landfill management and open dumpsites allow emission of greenhouse gases such as carbon (IV) oxide (CO_2) and methane (CH_4) released by decomposing wastes from beverage, petroleum, tobacco, food, or brewery industries; these gases contribute to global warming and cause climate change [38]. Also, hydrogen sulfide (H_2S) released from tannery, beverage, food, and tobacco wastes can cause environmental air pollution [38]. The complex nature of leachate that contains dissolved organic and inorganic toxic substances can cause eutrophication of surface water reducing water quality and amount of dissolved oxygen, which may result in death of aquatic life; leachates can also contaminate groundwater causing shortage of drinkable/usable water or disease and death [3].

6.2 Effect on human health

When landfills and open dumpsites are located near residential settlements due to improper site selection, residents within the vicinity of these sites experience health challenges than people living far away. A landfill that has not been carefully designed and constructed with necessary engineering techniques will contaminate the immediate surrounding due to the release of toxins and bioaerosols [39]. This contamination will lead to health complications such as diarrhea, stomach pain, cholera, flu, asthma, malaria, skin irritation, cough, and tuberculosis [39].

6.3 Effect on wild life

Animals are exposed to toxins from decomposing waste materials disposed at poorly managed landfills or open dumpsites through inhalation and ingestion. These exposure pathways can easily lead to both bioaccumulation and biomagnification of these pollutants in the respiratory track or guts of these animals, which at sublethal concentrations may cause neurological dysfunction, hemorrhaging, and infertility [38]. Lethal concentrations of toxic pollutants in animals may lead to instant death [38].

7. Control measures and Management of Industrial Wastes

The adverse effects of poor disposal of industrial wastes on man, animals, and the environment have resulted in an effort by industries to seek out measures to control and manage wastes generated within their facilities. In addition to the effects, economic and legal (in terms of host community court litigation) implications of waste generation and disposal affect industry-generated revenue. As stated in Ref. [40], the actual costs of generated waste in industry are purchase cost of materials, handling and processing costs, disposal cost, lost revenue, management time and monitoring costs, potential liabilities, and post-disposal segregation. In monitoring and controlling the management of industrial wastes, it is important to carry out pollutant characteristic evaluation so as to examine properties like phytotoxicity, toxicity level (environment and human), persistence, toxic activity, mobility, and bioaccumulation potentials of dioxins in wastes disposed at an engineering landfill facility by government agencies or private bodies so as to determine the effect of their release into the environment [9].

7.1 Waste management hierarchy

In industrial waste management, waste disposal is usually the last resort as industries may lose resources from disposing wastes with reusable or valuable materials often because an industry's waste is another's resource. A framework for deciding method of managing waste in the industry in order to focus on health, safety, environmental protection, sustainability, and cleaner generation of waste is the Waste Management Hierarchy (**Figure 15**) [40]. This hierarchy gives priority according to the waste management methods implemented in the industry and replaces the traditional 3R approach to waste management, namely reduce, reuse, and recycle [41].

The waste management hierarchy points waste management unit to develop a waste management roadmap by first preventing the generation of waste, which is the most preferred management method. When prevention is no longer practicable, waste reduction methods may be implemented through improved manufacturing techniques; after this, the unit would contemplate actions that promote waste reuse. Further, waste recycling options are considered. The next action of the waste management unit would then be energy recovery from the waste, while treatment and disposal are the final actions and the least preferable methods; all of these planning and actionable decisions could be carried out on a six-stage, inverted pyramid shown in **Figure 16** [40].

7.2 Collaborative or Co-operative industrial waste management (CWM)

Unlike municipal wastes, industrial wastes are invaluable or usable raw materials within and across many industries. Waste management techniques, involving reuse, recycle, or energy recovery from wastes, can either be carried out in an industry that generates such wastes or in another industry that has need and capacity to utilize the wastes as resource material or energy source [40]. Waste management carried out by

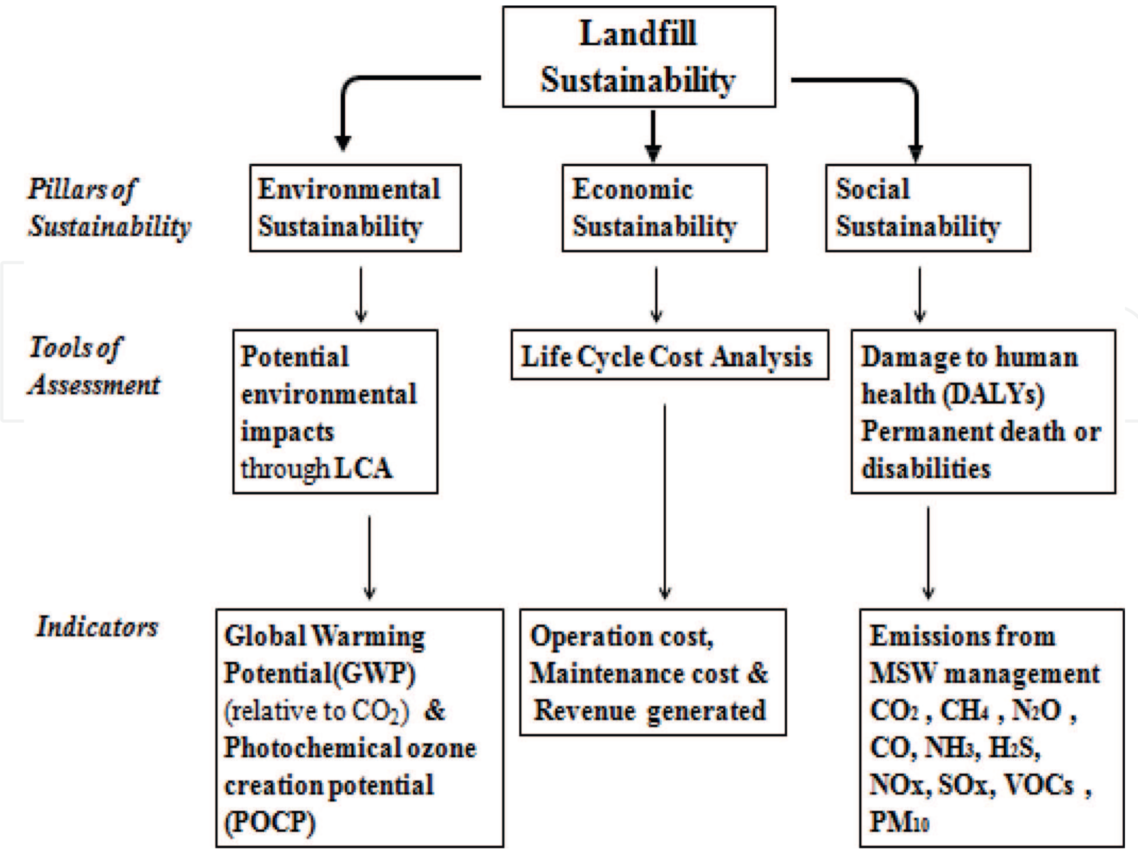

Figure 15.
Landfill sustainability assessment framework [33].

Figure 16.
Industrial waste management hierarchy [41].

a waste-generating industry through another industry is referred to as Collaborative Waste Management (CWM); this collaboration can be direct (**Figure 17**) or through an intermediary (**Figure 18**). CWM is an aspect of circular economy (CE), which is an industrial model that involves production, consumption, reuse, lease, repair, refurbishment, share, and recycling of industrial products in order to enhance retention of raw material value, majorly through circularity [42].

An illustration of collaborative industrial waste management is setup, according to Ref. [43], in Kalundborg, Denmark (**Figure 19**). It consisted of closely located

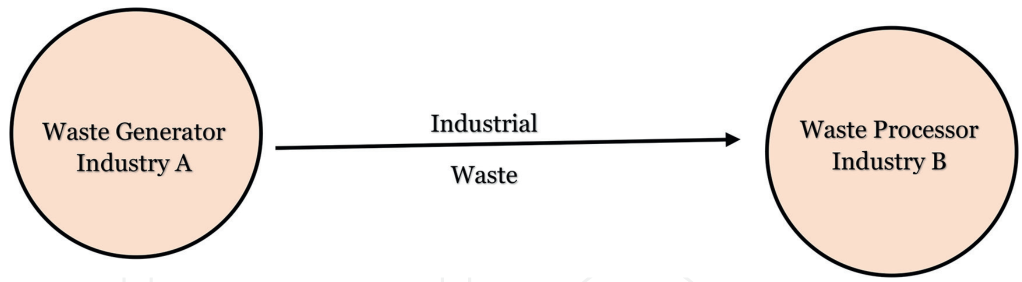

Figure 17.
Direct industrial waste management collaboration [39].

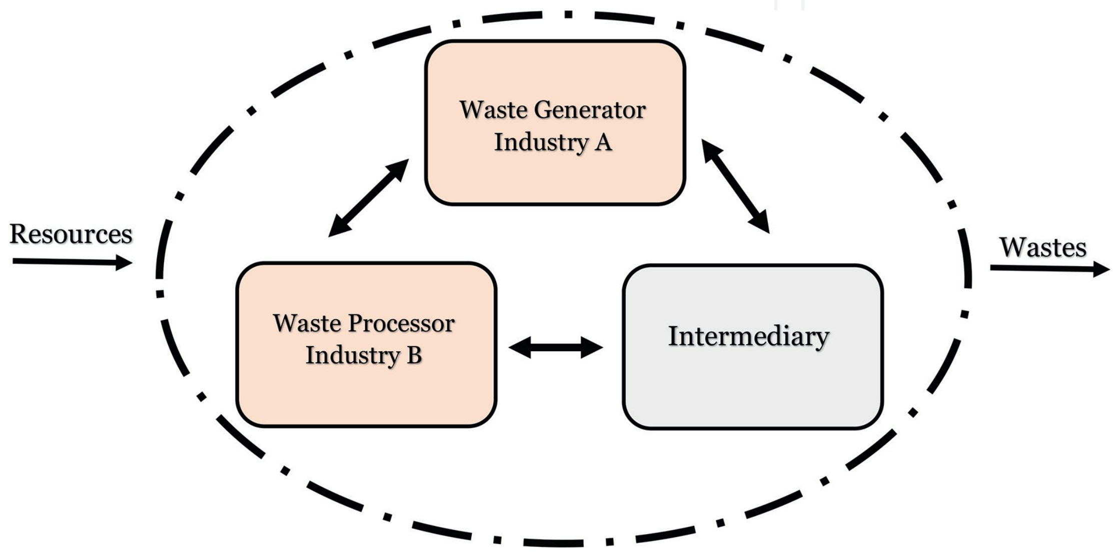

Figure 18.
Intermediary industrial waste management collaboration [39].

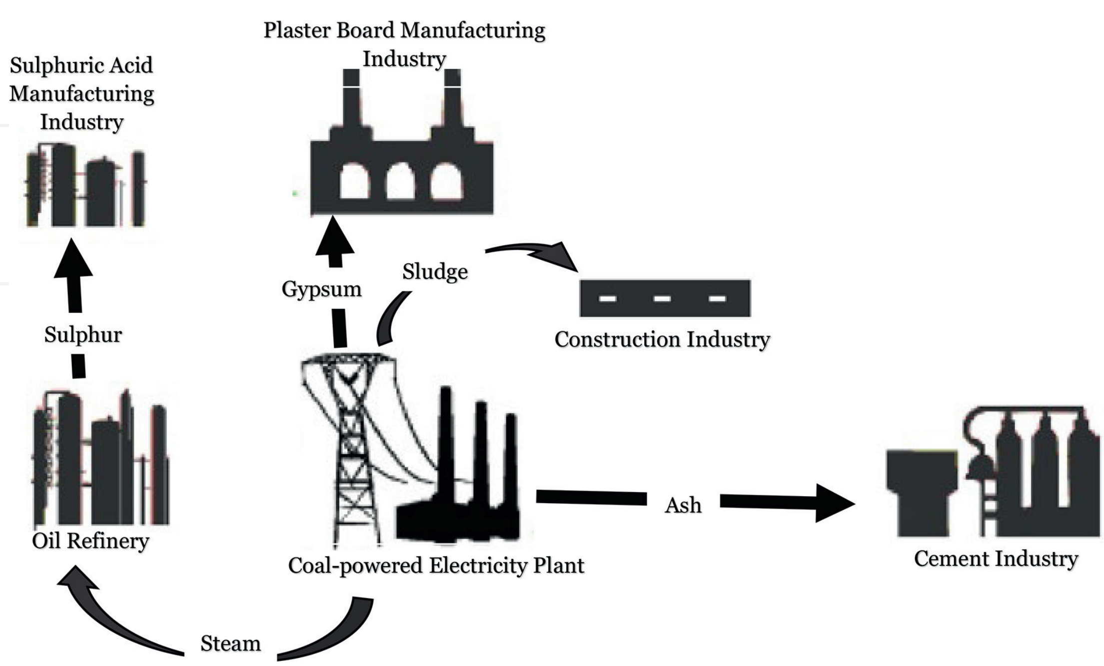

Figure 19.
Industrial waste management collaboration among industries [43].

industries including a cement factory, an oil refinery, a pharmaceutical firm, a coal-powered electricity station, a construction industry, and a plasterboard plant. In this setup, the gypsum, sludge, steam, and ash produced as wastes in the coal-powered plant are used raw materials in plasterboard plant, construction, oil refinery, and cement industries. Also, sulfur produced as waste in the refinery is used as raw material in the sulfuric acid manufacturing plant.

Other instances of CWM approach to industrial waste management can be seen in the use of waste oil and oil-containing materials from petroleum industry as alternative fuel in high-energy demand facilities like cement kilns or the use of spent oils from mining industry as raw material for the production of explosives, such as ammonium nitrate produced by the bulk mining explosive (BME) industry [40]. Also, sawdust, bark, wood scraps, planer shavings, and sanderdust produced in sawmill and woodwork facilities can be recovered and burnt for energy recovery in boiler facilities. There are advantages according to Ref. [40], which can be derived from using CWM method by industries. These advantages can be in terms of economic, social, safety, and legal gains and they include: (i) cost saving on waste disposal, (ii) improved company image with host community, (iii) reduced risk of liability, and (iv) public health and environment benefits.

8. Industrial waste landfill regulations

Regulation, as it relates to industrial waste landfills, refers to the directives or rules made and monitored by a government agency in respect of landfill planning, design, operation, and management. The importance of landfill regulation is to achieve the desired overall environmental health outcome and to reduce the negative impact of landfilling on the environment. The government, which is the major player in making and monitoring adherence to landfill regulations, recognizes that for a new landfill facility, environment protection is achieved through a combination of good planning and a thorough approach to design, operation, and management practices [44]. It is the opinion of Ref. [44] that there is no suitable alternative for selecting an appropriate site and adopting current management techniques to protect environmental integrity of the site. In the case of existing landfills, since the chance to select the best site is long gone, government priority is to ensure that the landfill facility is operated in a way that it minimizes environmental impact, and achieves efficient site remediation. For existing landfills, Peck [44] noted that performance-based approach to management of landfills encourages landfill operators to use their initiative to develop solutions suitable to their landfill operations. According to Peck [44], this approach acknowledges that retrospective design and construction techniques of achieving desired environmental outcomes from a landfill operation could put undue burden of costs on the operators, which, in most cases, is passed onto waste generators *via* disposal fees.

Although the government makes landfill regulations, these environmental rules have to be formulated with wide consultations and bargaining between government agencies and the industry; this is called public private partnership (PPP) for industrial waste management [45]. As stated by Wakiyama [46], industry associations that wield a strong influence on their members are selected to be participants in the formulation of regulatory policy. Government agencies depend on these associations' input to provide information and to measure the costs and feasibility of environmental standards [47]. The PPP allows consideration of industry interests and views in the formulation of regulations so that economic costs and consequences of proposed regulations are accounted before they are put into effect [47]. Once regulations are approved after consultation with industry participation, noncompliance is then monitored and sanctioned by government agencies [47]. When seeking to develop a PPP in industrial waste management projects, the landfill host community's environmental peculiarities are to be taken into account. These peculiarities may include considerations for public health, land ownership, economic and social benefits of the landfill, standards, and accountability, among others [48].

There are essentially two areas of environmental protection regulation for landfills and these are landfill planning and operation. The regulation at planning stage involves obtaining approval for a new landfill or an extension of approval for an existing landfill. Issuance of approval by the government requires that the landfill operator provides a detailed explanation of how the new or existing landfill will directly or indirectly impact the local environment in a document called environmental impact statement (EIS) [44]. The government may achieve operational regulation through issuance of waste licenses whose details are set out in a waste management act such as the Waste Minimization and Management Act of 1996 [49]. A license for operating landfills is required depending on the location of the landfill facility and type of waste received [44]. Typical waste license may include the following criteria:

Location criteria: Landfill location is the single most important determinant of the level of environmental risk posed by a landfill and perfect landfill location is the most efficient environmental management tool used to prevent degradation [44]. This regulation criterion sought to determine early on in the selection process, whether a proposed site is subject to environmental constraint or is of environmental value that it should not be considered as a potential landfill site; in other words, whether the proposed site is environmentally sensitive [44]. For protection of host environment, the location criteria set out steps to be taken when selecting a landfill site, with particular emphasis on carrying out topographic, hydrogeological, geological, and meteorological evaluations to determine the appropriateness of the site [44]. Furthermore, a formal EIS is to be prepared and submitted by the landfill operator if a proposed site will be used for disposal of industrial solid wastes that comprise: about 110,000 tons per annum of nonbiodegradable wastes that are likely to cause flooding or negatively impact drainage, more than 1000 tons per annum of sludge and above 198 tons per annum of other wastes; or the proposed site will be located as follows: within 100 meters of wetlands, coastal dune fields, natural water body; in an area of sodic or saline soil, high permeable or wettable soil, acid sulfate laden soil; within a drinking water catchment or an estuary where sea entrance is intermittently open or on a floodplain; and within 250 meters of a residential area not associated with the landfill site or likely to affect the infrastructure of the neighborhood where the landfill is sited as a result of noise, air pollution, visual impact, traffic, or vermin.

Type of waste and quantity criteria: Waste types disposed at a landfill account for the potential pollutants and likely severity of impact on the environment [44]. For a C&DD landfill that receives inert materials such as construction and demolition wastes that have no potentially hazardous characteristics, environmental risks are generally limited to noise, dust, and sediments, which can readily be controlled thus the criterion here specifies that inert waste landfills must not dispose wastes mixed or contaminated with any other material [44]. Industrial solid waste landfill receiving non-hazardous, degradable waste materials is likely to cause air (odour) and soil (leachate) pollutions as major environmental risks and thus, requires careful management [44]. For these landfills, this criterion provides that solid wastes shall contain less than 200 g/ton of hazardous wastes only and that all solid wastes must have an angle of repose above five degrees (5o) and also must not contain free liquids. Hazardous waste landfills pose the most significant environmental management challenges due to their characteristics and huge potential to cause harm. According to this criterion, hazardous waste landfills must only accept wastes classified as hazardous. These wastes must first be tested, treated, and must meet relevant waste acceptance criteria (WAC) before disposal at the landfill [44].

Environmental risks posed by a landfill can also be gauged by the quantity of waste received at the facility. If a landfill is well located and receives small amount of inert solid wastes, such facility will have minimal impact on the environment, but this is not the same with a facility that receives large amount of waste materials [44]. According to the waste type and quantity criteria, inert waste landfills that receive above 20,000 tons of waste per annum will have to be licensed regardless of their location. Also, 5000 tons per annum capacity solid waste landfills are required to be licensed irrespective of their location. But for hazardous waste landfills, they are required to be licensed regardless of the quantity of wastes received or their location; this criterion is in addition to other special requirements that may be stated by the government regulatory agency in the future regarding disposal of hazardous wastes [44].

According to these regulatory schemes, some facilities will not require licensing due to the relatively small amount of waste they receive and their appropriate or remote location, which indicate that they do not pose a significant environmental risk. The government notwithstanding recognized that if these relatively small facilities are not properly managed, localized environmental damage may result. Thus, it is required that operators make annual notifications to government agencies concerning the quantity and type of waste received, location, and ownership details of the landfill facilities [44].

9. Conclusion

Industrial wastes are unavoidable waste materials generated from industrial manufacturing processes. Many of these wastes materials have characteristics such as toxicity, ignitability, corrosivity, or reactivity, making them not only hazardous but also potential human and environmental health risk factors; although some industrial wastes are nonhazardous. The hazardous nature of industrial wastes has made disposal an important aspect of industrial operations. There are various methods by which industries manage and dispose their wastes but disposal at landfills remains the most practiced due to advantages such as large volume storage, inexpensive operational and maintenance costs, over other disposal methods. Landfilling operations, however, can lead to public health risks if poorly managed or designed due to the formation of by-products like biogas and leachate. Engineering or secure landfill design has features to mitigate contamination from landfill by-products and reduce environmental degradation by preventing leachate from seeping into groundwater and trapping biogas for energy production.

Modern industrial waste management technique focuses on retention of waste material values through reuse by same or other industry as raw material. This technique, called collaborative industrial waste management (CMW), is a subset of circular economy (CE), which is a model employed by large manufacturing industries to harness maximum economic, safety, social, and legal gains from their operations. It is important to operate landfills in a sustainable manner to reduce their negative impact. Also, regulation of landfill operations by the government is necessary to achieve desired environmental health and to mitigate environmental degradation occasioned by landfilling.

Acknowledgements

The authors wish to acknowledge the contributions of Department of Chemical and Polymer Engineering at Lagos State University (LASU) and Department of Chemical and Petroleum Engineering at University of Lagos (UNILAG) for permission to use some of the academic resources consulted for the production of this work.

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

The author wishes to thank IntechOpen for the opportunity to publish their work.

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