Chapter 8

Municipal Solid Waste Management and Energy Recovery

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Abstract

The contribution of this chapter is to deepen and widen existing knowledge on municipal solid waste (MSW) management by analyzing different energy recovery routes for MSW. The main aspects related to the composition of waste are addressed, as well as the technological routes for thermochemical and biochemical energy usage. Within the thermochemical route, incineration is currently the most utilized technology for energy recovery of waste, with generation of electricity and heat and also a decrease in the volume of the produced waste. Gasification and pyrolysis are alternatives for the production of chemical products from wastes. The biological route is an interesting alternative for the utilization of the organic fraction of MSW, as aerobic or anaerobic processes enable the production of biogas and of a compound that can be utilized as a fertilizer. Depending on the size of the population, composition of waste, and products to be obtained (energy or chemical), more than one technology can be combined for a better energy usage of waste.

Keywords: municipal solid waste, waste to energy, thermochemical route, biochemical route

1. Introduction

With the growth of world population and progressive increase in living standards, the consumption of goods and energy has also increased, along with land use change and deforestation, intensified agricultural practices, industrialization and energy use from fossil fuel sources. All of these have contributed to ever-increasing concentrations of greenhouse gases in the atmosphere, since the industrial era.

Municipal solid waste (MSW) is a manifestation of the unsustainable consumption of natural resources by humankind, which has led to—and continues to—the depletion of natural capital and environmental degradation.

Current global MSW generation levels are approximately 1.3 billion tons/year, and by 2025, these are expected to increase to approximately 2.2 billion tons/year. This represents a significant increase in per capita waste generation rates, from 1.20 to 1.42 kg per person per day, in the next 15 years (2018–2033). However, global averages are broad estimates only, as rates vary considerably by region, country, and even within cities [1].

On a global scale, 70% of MSW is landfilled, 19% is recycled, and only 11% is utilized in Waste-to-Energy (WtE) schemes—this occurs due to logistical and economic issues—such as primary fossil energy scarcity and landfill volume restrictions [2].

The concept of circular economy (CE)—while not entirely new—has recently gained importance in the agendas of policymakers, to address the aforementioned and other sustainability issues [3]. The aim of CE is to maintain the value of products, materials and resources as long as possible, to minimize the use of resources; in other words, CE is based on a "win-win" philosophy that states that prosper economy and healthy environment can co-exist [4].

WtE plants have a dual objective: reduce the amount of waste sent to landfills and produce useful energy (heat and/or power). The WtE supply chain provides a method for simultaneously addressing issues related to energy demand, waste management and emission of greenhouse gases (GHG), achieving a circular economy system (CES) [5].

Traditionally, WtE has been associated with incineration. Yet, the term is much broader, embracing several waste treatment processes that generate energy (electricity and/or heat), such as pyrolysis, conventional or plasma arc gasification, as well as nonthermal processes such as anaerobic digestion and landfill-gas recovery.

2. Municipal solid waste: general aspects

2.1. Definition

Municipal solid waste (MSW), also referred to as trash or garbage, consists of several items that are discarded after use, such as grass clippings, furniture, clothing, food scraps, product packaging, bottles, newspapers, appliances, paint, and batteries [6]. Construction, industrial, and hazardous waste are not considered MSW.

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2.2. Waste hierarchy and MSW composition

In recent decades, there has been increasing pressure on developed countries to reduce their waste associated with single-use discarded materials. The objective is to conserve natural resources, including energy (which is utilized for the production of such materials), and reduce the amount of materials disposed in sanitary landfills. The philosophy of waste management aims at decreasing the amount of waste generated by society and incentivizing reutilization and recovery of its energy content, when reutilization or recycling is not possible through biochemical or thermochemical technological routes.

Figure 1 presents a scheme based on the pyramid proposed by the European Commission. Different management strategies are ranked from most to least environmentally preferred.

Most WtE transformation processes require pre-treatment of MSW. The characteristics of the raw materials within solid waste are affected by several factors, which range from the storage method (influence of humidity), maturity (wide variety of waste within an excavated landfill), classification policies (which vary depending on the country), to name a few. Successful implementation of WtE conversion technologies depends considerably on the efficiency of the process, which, in turn, depends on the quality of the waste considered. **Table 1** presents the global average composition of MSW.

The recovery of energy and materials from MSW through the production of a refuse derived fuel (RDF) is one of the alternatives advocated by waste management planners and government regulations [9]. RDF is the product of processing MSW to separate the noncombustible from the combustible portion, enabling better reuse of materials and recycling of MSW, with the possibility of achieving higher efficiencies in energy recovery treatments. RDF is an efficient fuel with several advantages in comparison with MSW, due to its high calorific value, more homogeneous chemical composition, more convenient storage and handling characteristics, and less carbon emissions.

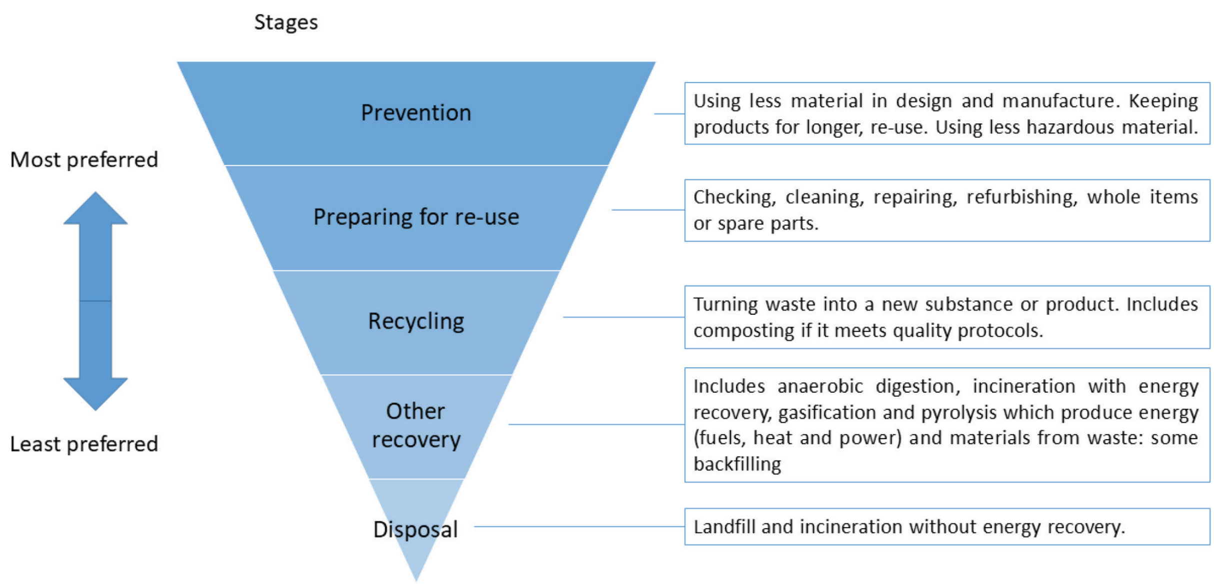

Figure 1. Waste hierarchy, adapted from [7].

Component	Fraction (%)
Organic	46
Metal	4
Plastic	10
Paper	17
Other	18

Table 1. Composition of global MSW [8].

Some studies have characterized the streams of materials involved in the RDF production process [9, 10], with descriptions on the characteristics of RDF in terms of composition and proximate and ultimate analysis [11, 12]. Also, the energy potential of RDF obtained from combustible solid waste has been evaluated by [13, 14].

Table 2 shows data compiled by [15] for the elemental composition of MSW and RDF.

The direct utilization of MSW in processes for the recovery of energy can lead to variable operation conditions, even unstable, with quality fluctuations in the final product. This is a consequence of the heterogeneity of the material regarding size, shape and composition. This is why firstly fuel is derived from waste, which is then utilized in the energy generation system [16]. For gasification and pyrolysis technologies, pretreatment is a fundamental requirement, which does not occur when considering plasma gasification and incineration.

With the objective of improving the handling characteristics and homogeneity of the material, the conversion process of MSW into fuels is constituted by different steps: trituration, sifting, selection, drying and/or pelletization. The least expensive and most

		MSW	RDF	RDF processed from landfill waste
Water content	wt% wet	34.2 [31.0–38.5]	10.8 [2.9–38.7]	14.4 [12–35.4]
Volatiles	wt% daf[a]	87.1 [87.1]	88.5 [74.6–99.4]	80.4
Ash	wt% dry	33.4 [16.6–44.2]	15.8 [7.8–34.5]	27.1
Net calorific value	MJ/kg daf	18.7 [12.1–22.5]	22.6 [1.1–29.3]	22
C	wt% daf	49.5 [33.9–56.8]	54.6 [42.5–68.7]	54.9
H	wt% daf	5.60 [1.72–8.46]	8.37 [5.84–15.16]	7.38
O	wt% daf	32.4 [22.4–38.5]	34.4 [15.8–43.7]	NA[b]
N	wt% daf	1.33 [0.70–1.95]	0.91 [0.22–2.37]	2.03
S	wt% daf	0.51 [0.22–1.40]	0.41 [0.01–1.27]	0.36

[a]Dry ash free.
[b]Not available.

Table 2. Composition of MSW and RDF: mean values and [min.–max.] [15].

well-established current practice to produce RDF from MSW is mechanical pretreatment (MT); however, different schemes can be used, as presented by [17].

3. Energy conversion technologies

The characteristics of waste are important when selecting a specific WtE technology. The energy recovery efficiency depends on variables such as technology and quality of waste. An optimized plant that treats preselected waste can recover two or three times more electricity and heat than a more traditional plant that treats raw waste [18].

There is a wide range of WtE technologies, biochemical and thermochemical, for the conversion of solid waste into energy (steam or electricity). Fuels such hydrogen, natural gas, synthetic diesel and ethanol can be utilized [19, 20].

The biochemical route, in the case of MSW, refers to anaerobic digestion, which consists of controlled decomposition by microbes to reduce the organic material. Biochemical processes are used in the treatment of waste with high percentages of biodegradable organic matter and high moisture content. Methane, fuel for electricity generation, steam and heat can be produced.

One of the disadvantages of the biological treatment is the preprocessing required to separate MSW. Biochemical conversion of waste can be grouped into four categories: anaerobic digestion/fermentation, aerobic digestion, composting, and landfill gas power (LFG). These technologies are the most economic and environmentally safe means of obtaining energy from MSW [21].

In thermochemical conversion, both biodegradable and nonbiodegradable matters contribute to the energy output. Incineration, gasification and pyrolysis are types of thermochemical conversion processes, which are fundamental and necessary components of a comprehensive and integral urban solid waste management system [22].

The main advantages of thermochemical processes include lower masses and volumes of waste, decrease in the space occupied by landfills, destruction of organic pollutants such as halogenated hydrocarbons, and decrease in the emission of GHGs due to anaerobic decomposition. When considering the life cycle, the use of waste as a source of energy generates less environmental impacts than other conventional energy sources.

With incineration, the energy value of waste can be recovered; however, pyrolysis and gasification can be utilized to recover the chemical value of waste. The derived chemical products, in some cases, can be utilized as inputs in other processes or as secondary fuels.

With the conversion of MSW into fuels, higher calorific values are obtained along with more homogeneous physical and chemical compositions, lower levels of pollutants and ashes, less excess air required for combustion, and better conditions for storage, handling, and transportation. Therefore, it is recommended to establish a balance between increasing production costs and the potential reduction of costs associated with designing and operating the system. **Figure 2** shows thermochemical conversion processes, the products involved, and energy and material recovery systems.

In the next topic, the main aspects of each of the mentioned routes will be analyzed.

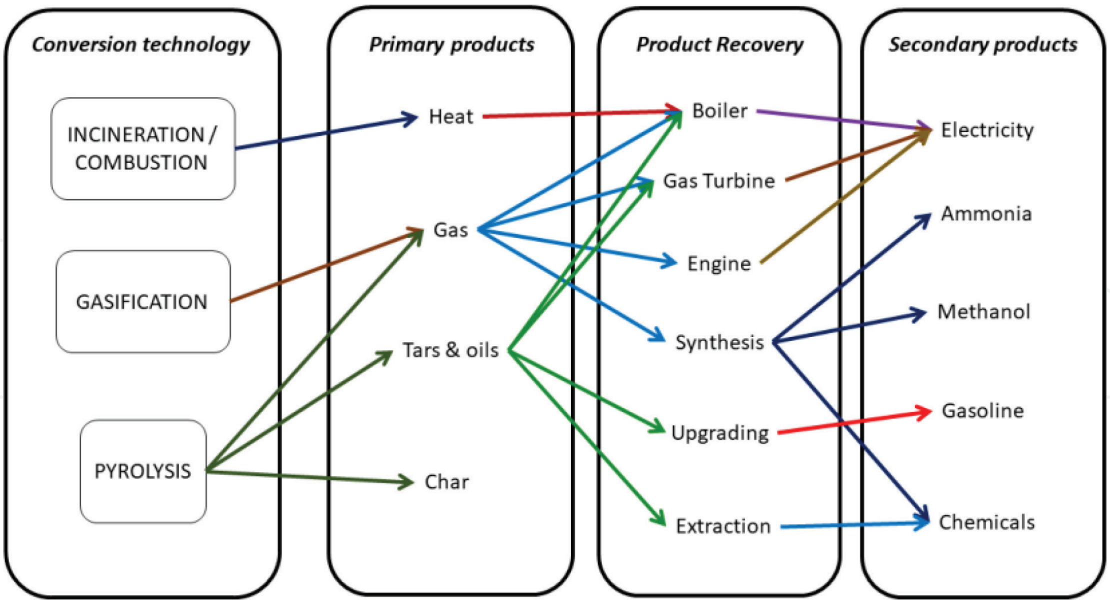

Figure 2. Thermochemical conversion processes and products, adapted from [23].

3.1. Thermochemical route

3.1.1. Incineration

Waste incineration is a specific treatment that reduces the volume of waste and its level of dangerousness, selecting and concentrating, or destroying the potentially harmful substances. Incineration processes can also offer the possibility of recovering the energy, mineral or chemical content of waste.

During recent decades, most industrialized countries with high population densities have employed incineration as an alternative procedure to controlled landfilling, for the treatment of MSW.

According to Ref. [24], the two main processes applied for the thermal treatment of waste are fluidized bed combustion and grate combustion. Another technological alternative is the rotary furnace or rotary kiln frequently employed in the field of waste treatment, for the combustion of hazardous waste in combination with other devices for gasification and pyrolysis [25].

Grate combustion, also known as mass burn combustion, is by far the most utilized, as it can handle larger items and only oversized materials have to be crushed. Fluidized bed combustion (as well as most pyrolysis and gasification processes) requires the waste to be shredded into small particles before being introduced in the combustion (pyrolysis/gasification) chamber [24].

The calorific value of the material to be incinerated and the polluting potential of the emissions generated are the main reasons for the evolution of incineration systems (higher combustion efficiencies and effective removal of contaminants).

Due to the heterogeneous nature of waste, some differences with respect to conventional fossil fuel power plants have to be considered in the energy conversion process. The efficiency of a coal burning cycle is generally around 40%, while the efficiency of a garbage incineration cycle varies between 20 and 25%, if operating in a cogeneration mode, and up to 25–35% in the case of power production only [8, 26–28]. In general, fuel quality (i.e., waste) and other technical conditions (e.g., plant size, low temperature sources, etc.) limit the electrical efficiency of incinerators. This means that more than 70–80% of the heat generated by waste combustion is rejected to the environment.

The conversion efficiency of steam energy into electricity increases with higher steam temperatures and pressures. However, when increasing steam temperature, the heat transfer surfaces are submitted to severe high-temperature corrosion, caused by metal chlorides in the ash particles deposited on the gas tubes and by high concentrations of chlorine and sulfur in MSW. Most chlorines are present in plastics (e.g., PVC), while fluorines are present in polytetrafluoroethylene (PTEF), along with other inorganic compounds. Corrosion limits steam properties to maximums of 450–500°C and 4.0–6.0 MPa, while the steam temperature can reach 600°C in a coal cycle [27, 29].

HCl is highly corrosive at high (>450°C) and low (<110°C) temperatures. The heating surfaces of radiant parts are protected by a resistant refractory material and/or welded high-alloy to prevent corrosive attacks in the furnace of the boiler system. The feed water should be preheated to a minimum of 125°C, before being sent to the boiler, to prevent low-temperature corrosion [29].

Beyond corrosion problems, another negative aspect related to WtE plants is represented by erosion, especially the abrasion of surface material responsible for the vertical wear and tear. This is primarily caused by the ash particles present in flue-gas, and erosion appears mostly in the area of gas redirection. Tube wear is caused by a combination of corrosion and abrasion.

The pollutants released with exhaust gases after the burning of the waste affect the efficiency of the boiler. In an MSW incineration plant, efficiency is influenced by the heat lost with exhaust gases and by corrosion, which means that the temperature of exhaust gases cannot be significantly changed. For this reason, until 2013, the maximum efficiency of a boiler was approximately 87% [30].

The incineration of MSW emits GHG such as carbon dioxide (CO_2), methane (CH_4), nitric oxide (N_2O), hydrofluorocarbons (HFCs), polyfluorocarbons (PFCs), and sulfur hexafluoride (SF). When the furnace is maintained under high oxidizable conditions, there is no CH_4 being emitted in the gases exiting the chimney. When primary air is supplied from the storage tank, CH_4 is oxidized to CO_2 and H_2O.

The pollutants emitted during incineration hinder the improvement of the steam cycle, but new technologies developed for the recovery of energy have managed to improve the overall efficiency of the plant. Some of the factors that have contributed the most to the improvement of new plants include two-second increase in residence time for dioxin destruction, high performance with mobile grills, utilization of new metal alloys and high-performance exhaust gas cleaning systems [31].

Most recent data from the Eurostat database highlight that municipal waste was treated differently in the EU 28 in 2014: 16.1% is composted (Eurostat shows it as biological treatment), 27.3% is incinerated (total incineration including energy recovery), 28.2% is recycled and 28.4% is landfilled [32].

Japan has 1172 incinerators for the treatment of 80% of MSW; approximately 71% of MSW is incinerated with energy recovery generating 1770 MW [33]. In the United States, there are 77 WtE power plants, of which 78% employ mass burn technology (60 facilities), 17% refuse derived fuel (13 facilities), and 4% utilize modular combustion (4 facilities). Of these facilities, 77% produce electricity (59 units), 4% export steam (3 units), and 19% cogeneration—or combined heat and power (15 units) [32].

LFG power represents one of the most readily available, cheap and relatively simple forms of WtE options. However, the carbon dioxide emissions from landfills per ton of MSW processed are at least 1.2 t CO_2, much higher than WtE plants. Considering all environmental performance criteria (energy, material, and land consumption, air and water emissions, risks), WtE is the most favorable solution [24].

3.1.2. Gasification

Gasification is the thermal conversion of carbon-based material into a mixture of combustible gases, called syngas. Gasification is used to convert solid materials such as coal, coke, biomass and solid waste into a gas, with average composition 15–30% CO, 12–40% H, and 4.5–9% CH_4. The lower heating value (LHV) of syngas is between 4 and 13 MJ/Nm^3, depending on the oxidizing agent used in gasification, operating conditions, among other factors [34]. From the syngas gas produced, different chemical intermediate products can be obtained, with different industrial uses. Energy can also be obtained, in the form of power, heat or biofuel. Gasification temperature is one of the most important operation parameters that affects the performance of the process, due to the balance between endothermic and exothermic reactions involved.

Ref. [35] compared different thermochemical conversion processes, and verified that gasification technology is the best choice considering energy and environmental perspectives. Gasification has attracted attention and gained importance in recent years, presenting higher energy efficiency and being friendlier to the environment.

One of the challenges of MSW gasification is the characteristics of MSW, with variable size and moisture content, and highly variable on calorific value [36].

The gasification of MSW is an effective technique to reduce the amount of waste, and is relatively faster than the conventional processes (more residues can be treated in less time). The process of integrated gasification and combustion emits dioxin and furan within acceptable limits established by national and international agencies [37].

Although gasification has been employed for over 200 years, gasification of MSW is still in its early development stages. Some companies are developing smaller, compact gasifiers designed to be used by cities, towns, and military bases. Companies engaged in waste gasification and the characteristics of gasification plants can be consulted in the Global Syngas Technologies Council Database (GSTC) [38].

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Plasma gasification is a technology suitable for MSW that uses a specific type of allothermal gasifiers. The heat that maintains the endothermic gasification reactions is provided by electrically generated thermal plasma (a plasma torch where an electric arc is created between two electrodes inside a vase and an inert gas is injected through this arc) [39].

The plasma torch temperature varies between 2700 and 4500°C, which is sufficient to crack the complex hydrocarbons in syngas, and all inorganic compounds (glass, metals, heavy metals) are melted in a volcanic-type lava that becomes a basaltic slag after cooling. The advantage of this system is that the syngas is produced in high temperatures, which ensures the destruction of all dioxins and furans. More information about this technology can be found in Refs. [40, 41].

Table 3 shows why gasification is attractive among other waste-to-energy technologies, due to its high efficiency for electricity generation at a lower unit cost.

3.1.3. Pyrolysis

Pyrolysis is the thermal degradation of organic material in an oxygen-deficient atmosphere at approximately 400–900°C, producing gas, liquid and solid products. The yield and composition of the products are influenced by a range of pyrolysis process parameters, including the type of waste, reactor system, gas residence time, contact time, heating rate, temperature, pressure ranges, and presence of catalysts [43].

Due to the different operation conditions, pyrolysis can be classified into three main categories: slow, fast and flash pyrolysis.

Pyrolysis is a promising technology and is currently utilized in many regions of the world for MSW disposal and energy generation. The objective of MSW pyrolysis is to treat waste, reduce its volume and associated hazards, destroying potentially harmful substances. Pyrolysis can also involve energy recovery from waste, in the form of heat, steam, electricity, or fuel (e.g., oil, char, and gas).

There are several types of pyrolysis reactors for MSW treatment operating in different countries, of which the most common are fixed-bed, fluidized bed, and rotary kiln reactors. Fixed-bed equipment is easy to operate and control, but presents disadvantages such as uneven

Performance parameter	Incineration	Pyrolysis	Plasma gasification	Conventional gasification
Capacity (t/day)	250	250	250	250
Conversion efficiency (MWh/t)	0.5	0.3	0.4	0.9
Power generation capacity (MWh/day)	160	180	108	224
Unit cost/kWh installed	435	222	1000	125
Unit cost (US$/nominal ton/day)	500	160	960	112

Table 3. Comparison between different MSW thermal treatment technologies [42].

heating and discontinuous running. The fluidized bed reactor can operate continuously and presents some advantages, such as high heat transfer efficiency and manageable temperature, but the resulting pyrolysis gas presents low calorific value. The rotary kiln reactor presents high internal heating and good adaptability to MSW; however, this technology presents a difficulty associated with the sealing of connectors [44].

More details on typical pyrolysis reactors, problems and MSW plants and products can be found in Refs. [42, 45, 46].

3.2. Biochemical route

3.2.1. Anaerobic digestion

Anaerobic digestion consists of a set of processes in which microorganisms consume the organic matter present in waste, in the absence of oxygen. This process occurs naturally in some types of soil and in the sediments settled on the bottom of a body of water (e.g., rivers, lakes, oceans, and swamps), where oxygen cannot penetrate. Decomposition of the submerse biomass occurs at the bottom of hydroelectricity reservoirs, producing methane.

There are several chemical reactions associated with conversion processes, which are in chemical balance. Generally, although some authors classify the anaerobic digestion process in two or even three steps, it is more common to utilize four steps to describe the process, as depicted in **Table 4**.

The main aspects that influence anaerobic digestion are [48, 49]:

pH/alkalinity: methanogenic bacteria are sensitive to acid environments, and an increase in the pH will inhibit their growth. pH varies throughout the different steps of the process due to the generation of fatty acids, CO_2, and bicarbonates. pH correction is accomplished through the addition of a basic compound ($CaCO_3$, NaOH). The optimal range of pH is between 6.6 and 7.4.

Temperature: temperature is related to the growth of microbes, and therefore, its control is very important for optimal growth/development of microorganisms and performance

Step	Description
Hydrolysis	Organic polymolecules are cracked into standard molecules such as sugars, amino, and fatty acids with the addition of hydroxyl groups. This is accomplished by hydrolytic bacteria.
Acidogenesis	Sugars, fatty, and amino acids are converted into smaller molecules, with the formation of volatile fatty acids (acetic, propionic, butyric, and valeric acids) and production of ammonia, carbon dioxide, and H_2S as subproducts.
Acetogenesis	The molecules produced during acidogenesis are digested, producing carbon dioxide, hydrogen, and acetic acid.
Methanogenesis	Formation of methane, carbon dioxide, and water.

Table 4. Description of the anaerobic digestion phases [47].

of anaerobic digestion. The process can occur in two ranges, mesophilic (25–40°C) and thermophilic (55–65°C). The mesophilic range is an interval of temperature conditions that enables bacteria to be more tolerant to changes in the environment, constituting more resistant microorganisms, but with higher retention times and lower production of biogas. This condition enables the use of simpler reactors, without complex control systems, with simpler operation strategies that entail lower capital costs. However, within thermophilic conditions, there is a higher production of biogas, with lower retention times. In these conditions, microorganisms are less tolerant to changes in the environment, which if occur, can compromise the production. A more complex, precise control system is required, with higher capital costs associated.

Substrate concentrations: an increase in the organic load can lead to an excessive production of acids, which can act as inhibitors for other reactions and cause lower biogas yield.

Partial H_2 pressure: an increase in pressure can lead to system collapse due to accumulation of acids.

C/N ratio: in the anaerobic digestion process, carbon corresponds to the source of energy, and nitrogen enables microbial growth. The optimal ratio between carbon (C) and nitrogen (N) varies between 20 and 30. High values of the C/N relationship are associated with a fast consumption of nitrogen, which can limit microbial growth and reduce gas production. Lower C/N values lead to accumulation of ammonia, which affects the pH of the reactor.

Anaerobic digestion adds value to MSW, generating an overall positive impact on the environment as it avoids a series of issues (negative impacts) associated with the natural decomposition process that occurs in landfills, besides enabling the substitution of other fossil raw materials.

The process of anaerobic digestion can occur in controlled environments, such as in biodigesters, which recover energy from waste, and in sanitary landfills. Sanitary landfills are locations for the controlled disposal of waste, reducing its negative environmental impact, and for the control of lixiviate material. Some landfills generate electricity from the biogas produced.

Biogas production from organics within the MSW stream is in the range of 100–150 m^3 of biogas per ton of source separated organics (SSO) [50].

3.2.1.1. Types of biodigesters

There are currently several commercially consolidated technologies for biodigestion, such as the Dranco, Valorga, Kompoga, BTA, and Linde-BRV systems. These technologies are widely employed in Europe, with 118 plants in operation, which totalize a combined treatment capacity 5.12 million tons of MSW per year. The Valorga system alone presents an installed capacity of 2.19 million tons of MSW [51, 52]. **Table 5** presents a summary of size, capacity and applications of anaerobic digestion systems.

More details about WtE such as biogas technologies, process, efficiencies, economic, and environment aspects can be found in Refs. [50, 54].

Size	Capacity (t/year)	Electricity production	Typical applications
Small	Up to 7500	25–250 kW_e	Residential and agricultural (farms) applications
Intermediate	7500–30,000	250–1 MW_e	Agricultural applications or digestible waste production facilities
Large	Above 30,000	Over 1 MW_e	Centralized, with several mixed raw materials (municipal, industrial)

Table 5. Size, capacity, and applications of anaerobic digestion systems [53].

3.2.2. Landfill gas

Landfill gas (LFG) is formed when organic wastes decompose anaerobically in a landfill. Although LFG gas is generated under aerobic and anaerobic conditions, the initial aerobic phase is short-lived and produces a gas with a much lower energy content than does the long-term anaerobic phase which follows.

There are several models developed to estimate the amount of biogas that can be produced from a sanitary landfill. According to Ref. [55], these models can be divided into:

Zero-order models: generation of biogas is considered constant throughout time, with no influence of age and type of waste.

First-order models: consider waste characteristics, such as humidity, carbon content, MSW availability.

Second-order models: utilize the reactions that occur during organic matter degradation, constituting a second-order kinetic model.

Numerical and mathematical models: consider the different variables involved in the process, and require a higher number of inputs.

The most utilized models for the estimation of biogas production from waste are the first-order models, of which the IPCC and LandGEM [55] are the most employed.

3.2.2.1. Intergovernmental panel on climate change (IPCC) model

Developed by the Intergovernmental Panel on Climate Change (IPCC), it is a first-order decay model (revised equations of IPCC-2006). It considers the degradation rates of waste and generation of methane throughout time. In the case of MSW, information on the different types of residues (food scraps, paper, wood, textiles, etc.) is required [56]. According to the IPCC model, the amount of methane produced is given by:

$$Q_{CH_4} = \sum_{t=S}^{E} n\left\{\left[\left(\frac{1-e^{-k}}{k}\cdot k\cdot RSUT_n\cdot RSUF_n\cdot L_{0(t)}\right)\cdot e^{-k(t-x)}\right]-R_x\right\}\cdot(1-OX) \quad (1)$$

Q_{CH_4} is the amount of methane generated per year (t CH_4/t waste), S refers to the beginning of landfill operation, E refers to the end of landfill operations, n is the considered year, and k is

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the methane generation constant rate (y^{-1}). $RSUT_n$ is the amount of MSW generated in year n (t waste/year), $RSUF_n$ is the fraction of MSW destined to landfilling in year n (dimensionless).

$L_{0(t)}$ is the methane generation potential, expressed as:

$$L_{0(t)} = MCF_{(t)} \cdot DOC_{(t)} \cdot DOC_f \cdot F \cdot (16/12) \tag{2}$$

$MCF_{(t)}$ is the methane correction factor and reflects the management of the disposal locations (dimensionless), $DOC_{(t)}$ is the degradable organic carbon (t carbon/t waste), DOC_f is the fraction of degradable carbon (dimensionless), F is the methane fraction within biogas (dimensionless), 16/12 is the conversion ratio between carbon (C) and methane (CH_4) (dimensionless), $R(n)$ is the recovered methane (t CH_4/t waste), n are the years considered, and OX is an oxidation factor (reflects the amount of methane in the residual mass that is oxidized in the soil and cover layer (dimensionless).

3.2.2.2. LandGEM model

The Landfill Gas Emissions Model (LandGEM) was developed in 2005 by the Control Technology Center of the Environmental Protection Agency of the U.S.A. This mathematical model is utilized to estimate the amount of landfill gas generated in a specific location, allowing for variations to be introduced. Besides methane, 49 other compounds can be calculated. It is based on electronic worksheets that use a first-order decay equation. It is considered that methane generation peaks soon after initial disposal of waste and the methane generation rate decays exponentially as organic matter is consumed by bacteria [55]:

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k \cdot L_0 \cdot \left[\frac{M_i}{10}\right] \cdot (e^{-k \cdot t_{ij}}) \tag{3}$$

Q_{CH_4} is the amount of methane produced per year (m^3/year), i is the time, in years, to be incremented, n is the inventory year, j is the time, in years/10, to be incremented, k is the methane generation rate ($year^{-1}$), L_0 is the potential methane generation (m^3 CH_4/t waste), M_i is the mass of solid waste received during year "I" (t/year), and t is the age of section "j" of waste M_i received during year "I" (years with decimal point, e.g., 3.2 years).

There is a great potential for electricity generation from landfill gas (biogas), as 1 ton of methane can be equivalent to 3.67 MWh—considering a conversion efficiency of 30%, this can be equivalent to 1.1 MWh_e [57]. This way, considering the ever-growing restrictions regarding MSW disposal along with the high volumes of MSW generated (with high energy potential), the use of anaerobic digestion has been the focus of several studies. The International Energy Agency (IEA) has a study group dedicated to biogas energy, Task 37: energy from biogas, with the objective of approaching the challenges related to economic and environmental sustainability of the production and utilization of biogas [58].

With the increasing necessity of promoting renewable energies, along with the emergence of new technologies that have lowered production costs, anaerobic digestion has been attracting the attention of developed European countries and also of populous countries such as India and China [1].

WTE technologies	Capital cost (US$/ton of MSW/year)	Operational cost (US$/ton of MSW/year)
Incineration	400–700	40–70
Pyrolysis	400–700	50–80
Gasification	250–850	45–85
Anaerobic digestion	50–350	5–35
Landfilling with gas recovery	10–30	1–3

Table 6. Cost estimates for different waste treatment technologies [60].

Another factor that contributes to the economic viability of anaerobic biodigestion is the progressive trend of countries adopting laws that prohibit the disposal of organic waste in sanitary landfills, demanding technologies that can effectively manage waste and recover the energy still contained within the covalent bonds of organic waste [58].

The study by Ref. [59] presented step-by-step, thorough calculations for landfill gas generation capacity, including the total amount of solid waste disposed, total organic matter, fractions of degradable organics, methane generated, methane captured, and finally, the amount of approximately 65,000 tons of captured LFG in 30 years. The leachate flow in the landfill was 8000 m^3/year. The landfill could produce approximately 135 GWh of electricity throughout its lifetime, with a global efficiency of almost 84%.

3.3. Economic aspects

Investment costs depend on the degree of complexity of the technology, as well as whether the system requires auxiliary processes such as pretreatment, gas cleaning, among others. **Table 6** presents cost estimated for different waste treatment technologies.

Regarding the costs associated with MSW disposal, biological routes present considerably lower costs than thermochemical routes. The facilities that utilize biological routes present simpler construction, when compared with thermochemical facilities. Besides, operational costs correspond to approximately 1% of the capital cost required.

4. Conclusions

Nowadays, it becomes more evident that mankind is facing serious difficulties regarding waste disposal and therefore can be its own victim. Waste disposal is unavoidable, but special, systematic efforts must be directed to establish a turnaround strategy.

One of the biggest challenges for modern society is establishing an effective strategy for the management and treatment of municipal solid waste. This strategy should consider, whenever possible, economic and environmental viewpoints. Global warming mitigation alternatives include the harvesting of landfill gas as an important waste management strategy.

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There are currently different technological routes for municipal solid waste, which could transform these from a challenge or a problem into a source of clean energy and useful recyclable raw materials. At the same time, the impact of waste on the environment would decrease, benefitting human health and natural resources.

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