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Review

Municipal solid waste generation and the current state of waste-to-energy potential: State of art review

Afzal Husain Khan [a], Eduardo Alberto López-Maldonado [b], Shah Saud Alam [c], Nadeem A Khan [d,*], Juan Ramon López López [e], Perla Fabiola Méndez Herrera [e], Ahmed Abutaleb [f], Sirajuddin Ahmed [d], Lakhveer Singh [g,*]

[a] Civil Engineering Department, College of Engineering, Jazan University, P.O Box 706, Jazan, 45142, Saudi Arabia
[b] Faculty of Chemical Sciences and Engineering, Autonomous University of Baja California, CP, 22390 Tijuana, Baja California, Mexico
[c] Department of Mechanical Engineering, The University of Kansas, 1530W 15th St., Lawrence, KS 66045, USA
[d] Department of Civil Engineering, Jamia Millia Islamia Central University, New Delhi 110025, India
[e] Facultad de Ciencias Químico-Biológicas, Universidad Autónoma de Sinaloa, Av. Las Américas S/N, C.P. 80000 Culiacán, Sinaloa, Mexico
[f] Chemical Engineering Department, College of Engineering, Jazan University, P.O. Box. 706, Jazan 45142, Saudi Arabia
[g] Department of Chemistry, Sardar Patel University, Mandi 175001, Himachal Pradesh, India

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ABSTRACT

The extraction of municipal solid waste (MSW) provides a significant opportunity to manage MSW while bolstering energy security. As a result, research in this area has gained traction over the last few decades. It appears that this route carries the potential to reshape the future of energy and environmental management. However, the technological, socio-economic, and legal challenges are the stumbling blocks that need to be overcome for the successful implementation of such technology. Therefore, this effort reviews the available literature to gather pertinent information on the benefits and limitations of the existing conventional and non-conventional MSW management methods, the challenges involved in their large-scale implementation, the opportunities that such technologies can create, and the governmental policies that need to be in effect to foster their implementation. To provide some perspective, this review presents the case studies from Brazil, India, and New Zealand where these technologies have been implemented with varying levels of success. A thorough comparison of these case studies should potentially highlight the areas of major concern that hinder WtE implementation. Overall, MSW management via WtE routes, e.g., chemical, biological, and thermal, are more effective at MSWM than conventional methods. It also becomes evident that MSW statistics (generation, accumulation, composition, etc.) can vary significantly based on geographical location, socio-economic factors, etc. Therefore, concrete strategies, perspectives, and roadmaps will be necessary to select the best technology for each situation. Finally, large-scale implementation of these WtE technologies would necessitate economic incentives and favorable governmental policies.

1. Introduction

The global population is growing at an annual rate of 1.05%, and at this rate, it will surpass 10 billion by 2057 [1]. Consequently, the per-capita waste generation is also growing proportionally, resulting in an increased generation and accumulation of municipal solid waste (MSW). In addition, rapid urbanization and economic development also promote the generation of MSW [2-4]. Estimates show that 2.01 billion tons of MSW are generated each year, of which 33% remains unmanaged. This poses a serious challenge towards environmental sustainability, and therefore, there is a pressing need for strategies to address the growing MSW worldwide [5-7].

The continuous growth in urban industrial waste and its complex composition makes its management difficult, and therefore, waste management has become one of the most challenging problems for modern society [8-11]. In addition, mismanagement of MSW also poses risks to the community and creates several issues for both society and the economy [12-14]. Furthermore, the over-reliance on MSW

* Corresponding authors.
E-mail addresses: er.nadimcivil@gmail.com (N.A. Khan), lucki.chem09@gmail.com (L. Singh).

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landfilling has also a troubled society with financial, health, and safety concerns [15-18].

To overcome these challenges, it is imperative to develop environment-friendly methods for the management of MSW [19,20]. Therefore, recycling, landfill gas recovery, composting, and energy recovery methods have gained traction to minimize MSW. Among these methods, the waste-to-energy (WtE) methods appear to be the most promising due to the following reasons:

1. It is a resource recycling method that can help reduce waste in landfills [21-23].
2. The energy generated from MSW can potentially offset the use of fossil fuels for energy production, thus, boosting energy security, minimizing emissions related to fossil fuel extraction, and minimizing land use [24].

This paper provides an overview of the generation, composition, and embedded energy content of MSW. In addition, the main aim of this paper is to highlight the WtE methods that can be employed to harness energy from MSW. Furthermore, the challenges associated with MSW WtE methods are also listed to highlight the limitations of these methods. Nonetheless, examples of their implementation in developed countries and their potential application in developing countries are provided.

2. Global MSW generation and challenges

Current estimates put the annual global MSW production at 2.01 billion tons. Approximately 33% of the generated MSW is not handled properly [1]. Unmanaged MSW is a common problem in developing countries. For example, India generated ca. 52.9 million tons of MSW in 2018, followed by 53.2 million tons in 2019 [1]. Since solid waste management (SWM) in India is still evolving and has improved over the years, the percentage of waste processed annually in India is relatively low (~60%) compared to developed nations. This problem worsens as India's population grows, generating an increased amount of waste that results in a more significant proportion of unmanaged MSW [17,25-27]. Eventually, unmanaged MSW creates multiple issues for SWM in India, with the collection, storage, and transportation of MSW becoming the worst affected areas that require immediate attention [28-30]. Therefore, it is inferred that SWM in developing countries is generally flawed due to multiple reasons. First, the compositional variety of MSW necessitates adequate handling procedures that are both costly and time-prohibitive [31,32]. Second, developing countries usually lack MSW collection-at-doorstep facilities and suffer from lower recycling rates [33].

Consequently, a small amount of MSW is processed while the rest is unscientifically disposed of in landfills [34]. Third, developing countries lack adequate facilities to treat the growing volumes of MSW [34]. Often, this results in unregulated dumping of MSW on land that contaminates both water (e.g., groundwater) and air and poses a threat to humans, animals, and plants [35]. Therefore, significant effort is required to implement robust solid waste management techniques with minimal unmanaged MSW [36,37].

In addition, WtE methods can help alleviate the stress on fossil reserves to meet the energy requirements of the growing global population while minimizing the local contamination resulting from unmanaged MSW and its unscientific disposal [38,39]. Therefore, WtE methods can help developing nations build circular economies in the future [1]. However, WtE methods can be influenced by place, environment, geographical, and other socio-economic considerations [40]. Therefore, it becomes imperative to study and understand WtE methods in more detail to propose large-scale, long-term implementation of adequate WtE technologies for developing nations. Before moving to WtE methods, it is essential to discuss the benefits and shortcomings of some prominent MSW collection and treatment procedures and how WtE methods can overcome these limitations.

3. MSW's prominent collection and treatment methods

MSW can be used in various ways; however, considering it as a resource for energy conversion is the most vital. Two processes can be used for this purpose, the biological process used in sanitary landfills and the thermal process in different versions. Here we describe the most updated methods, which offer several niches of opportunity, such as water pumping, public lighting, transportation, etc. A few, of course, according to the characteristics of the waste generated in quantity and composition.

A critical step is collecting before waste treatment and utilization (separation methods and collection). It has been reported that the collection and transportation processes represent a high cost within the total cost of overall waste management, which is why it is important to have optimized systems to carry out these activities in such a way that, on the one hand, the cost is reduced and, on the other hand, by being more efficient, they benefit both the environment and the subsequent stages up to their processing. Fig. 1 shows the different types of separation and collection currently used, with some improvements.

Nowadays, waste separation and storage methods are door-to-door, curbside points, drop-off points, and storage in mixed waste bins without source separation [41,42]. In the door-to-door system, citizens separate recyclable waste from organic waste in plastic bags and deposit them in front of their homes [43]; it is essential to point out that some countries, mainly in Latin America, use this method but do not separate the waste, which means that the waste cannot be used with current technologies [44]. In the curbside collection system, again, citizens perform waste separation, but now it is placed in containers located at a certain distance, usually in a range between 50 and 100 m [45]. On the other hand, at drop-off points, citizens collocated the separated waste in larger capacity containers located on the street between 500 and 1000 m away from inhabited areas [46]. Finally, in the mixed waste collection, MSW is placed in containers without being separated; this activity is carried out by recycling personnel. From there,t is transported to the transfer and final disposal centers [41]. The existing collection systems can be classified as formal, informal, and formalized modalities [41]. Traditional collection occurs when citizens separate their waste, and collection is carried out by municipal personnel or standard private service, while recyclers carry out the informal waste separation process without any formalization; the third modality is a combination of the two previous ones with a formalized system.

To improve the separation-collection process, different strategies have been employed. Several authors have reported using life cycle assessment and other mathematical models to improve the MSW collection stage considering the technical and economic characteristics of the generating country, such as a comprehensive database on infrastructural characteristics, waste generation, composition settlement structure, and financial parameters. The model can be even more complex, adding other factors like distances traveled by vehicles, number of houses or bins to collect, number of waste truck trips, labor hours, seasonal variation, etc. In this sense, mathematical programming, geographic information systems (GIS-based network analysis), and even artificial intelligence algorithms have been used to optimize MSW collection [47-51]. Currently, the automation of MSW sorting plants has been tested by complementing or replacing manual sorting with that performed by a robot with artificial intelligence [52]; another revolutionary proposal is the subway collection of waste by vacuum, which emerges as a solution for areas of difficult access [53].

4. Current WtE methods adopted by countries

4.1. Traditional WtE methods

An efficient waste management system requires WtE facilities that

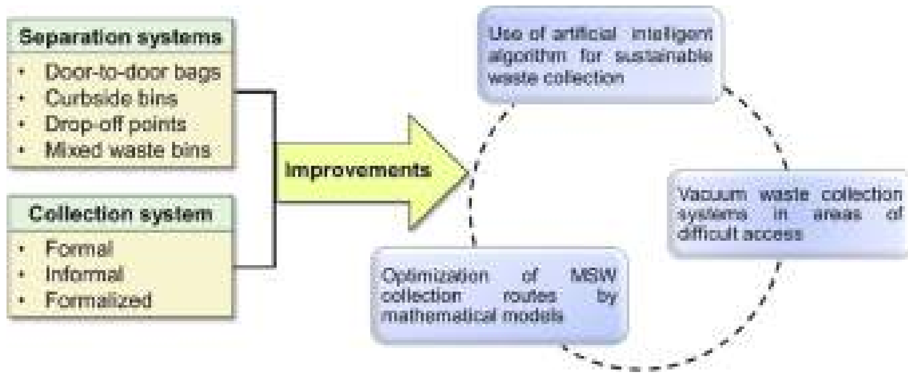

Fig. 1. MSW separation and collection systems.

are safe and equipped with advanced technology to reduce the weight and volume of waste and generate clean, low-carbon energy from an energy perspective.

Some technologies have been used for many years, such as the case of landfills and incineration. However, our society has evolved due to population growth, needs, and technological development that has emerged in different areas, resulting in a complex waste generation that cannot be treated with traditional treatments. This need has given the guideline for generating new technologies or modifications to existing ones. WtE technologies represent an environmental and economic opportunity. If the appropriate technologies and processes are applied, valuable products such as biogas, liquid oil, char, biodiesel, bioethanol, compost, digested, heat and steam can be extracted.

Traditional WtE can be classified as biochemical conversion, thermal, and chemical & mechanical methods (Fig. 2) [54]. The biochemical conversion (anaerobic digestion, ethanol fermentation, landfill with gas capture, and composting) involves using microorganisms like bacteria or enzymes to break down organic matter. Thermal treatments (incineration, pyrolysis, and gasification), on the other hand, use waste as feed for conversion into energy, products, and by-products [55] chemical & mechanical methods (Esterification and chemical & Mechanical biological treatment) employ esterification and transesterification reactions to obtain biodiesel from oily wastes or combine mechanical and biochemical processes to bring recycled materials biogas digested like in MBT technology.

4.1.1. Biochemical conversion

4.1.1.1. Anaerobic digestion (AD). Anaerobic digestion occurs when the organic fraction of municipal waste decomposes due to the action of bacteria and the absence of oxygen. During this process, biogas is generated and can be used to create energy and a nutrient-rich digested that can be employed as a fertilizer in agricultural soils. The AD occurs via three stages; first, the organic matter composed of proteins, carbohydrates, and fats breakdown into less complex molecules (amino acids, sugars, and fatty acids. In the next stage, through acidogenesis, sugars and amino acids are transformed into even simpler products such as carbon dioxide, hydrogen, ammonium, and organic acids. Finally, methanogenesis occurs in stage three, where organic acids are converted into methane gas.

In some countries, the processing of organic matter for energy use has increased in recent years, for example, in the United States of America [56] Iceland [57], and Malaysia [58]. Optimizing the AD processes will make it possible to generate electricity, reduce landfills, and promote a circular economy.

4.1.1.2. Ethanol fermentation. Ethanol can be obtained as a product of fermentation. The glucose and fructose present in the organic fraction of the residues (mainly peels from fruits such as banana, papaya, and citrus) are converted by enzymatic action into ethyl alcohol. After fermentation, the product undergoes a distillation process to obtain anhydrous bioethanol, an alternative fuel [59]. Some strategies have been used to increase the amount of biofuel received. Some of them are

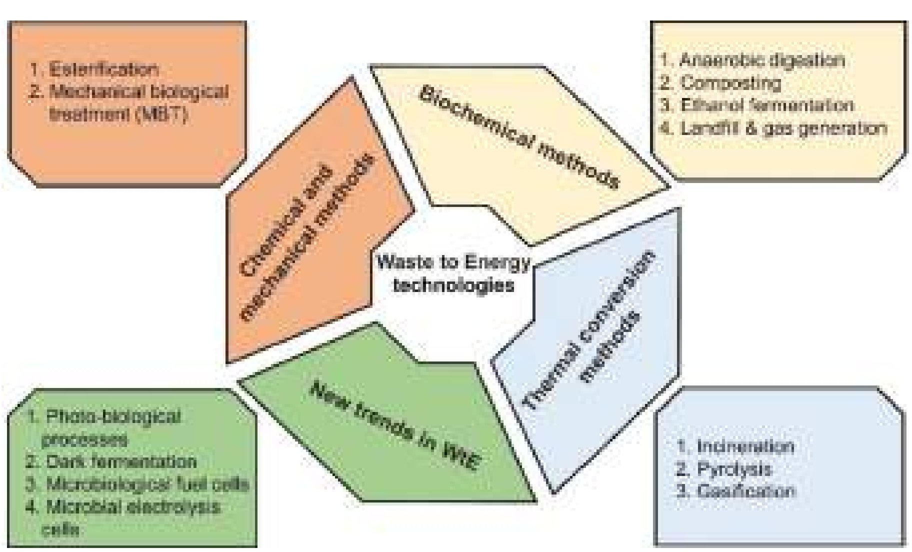

Fig. 2. WtE technologies classification.

pretreatments with alkali, acids, or eutectic solvents [60-62] to increase the solubility of the cellulose due to the complex mixture of food waste. In contrast, others focus on using different types of catalysts [63] and combining them with ultrasound [64]. The challenge of this WtE technology lies in achieving commercially competitive bioethanol prices.

4.1.1.3. Landfill with gas capture. Historically, the landfill has been used as a method for waste treatment; even with recycling and waste processing techniques, this system prevails mainly in developing countries due to the economic aspect. A properly constructed, well-managed, and operated landfill can significantly reduce waste in volume and weight and generate biogas.

The landfill consists of a natural or artificial trench subjected to preparation processes, including compaction, waterproofing, and leveling. It also has equipment for the drainage system, leachate pumping, monitoring, capture, and biogas extraction. The operation of the landfill is divided into two stages. The first corresponds to the initial operation where the MSW is placed, and biogas production begins through aerobic and anaerobic processes. The second is called the closed stage, where the volume of waste generates its maximum biogas production. The biogas generated is a mixture of gases containing mainly CH_4 (48–65%), CO_2 (36–41%), and in smaller quantities, N_2 (<1–17%), O_2 (<1%), and water vapor (6–6.5%) [65] and can be used as an energy source in different equipment such as in gas turbines, burning machines, and steam boilers for electricity or heat production. Some cities have successfully implemented landfill-to-energy (WtE) systems, such as Jakarta in Indonesia, with the extraction of 0.05 to 0.40 m^3 per kg of the landfilled MSW [66] and Salinas Victoria in Mexico, with an average CH_4 production of 2932 ft^3/min (maximum flowrate 4072 ft^3/min) and an energy generation of 32.396 million kWh/year and hot water/steam production of 63.990 million BTU/year [67]. While in Itabira, State of Minas Gerais, Brazil has used microalgae for the bioremediation of landfill leachate with the possibility of using the biomass for different purposes [68]. The main factors affecting biogas generation are waste quantity and composition, time (gas generation period), temperature, and moisture content. To improve CH_4 production, this technology can be combined with other thermal WtE such as incineration or pyrolysis and used to generate biomass.

It is essential to highlight that since it is one of the most widely used technologies worldwide and due to the potential risk it represents for people's health, constant monitoring is required during operation (active), and once it is finished (closed), monitoring is regulated according to the government policies of each country, in general, it is stipulated that it must be carried out for 30 years once closed. The parameters that can be monitored in an open or closed landfill are meteorology (precipitation, air temperature, and pressure, wind speed, evaporation, and relative humidity), leachate (quantitative and qualitative analysis), ground water (level and quality), gases (methane, carbon dioxide, oxygen, hydrogen sulfide, and hydrogen), structure, cover slope and stability of the landfill (waste covering area stability), surface water (quality), protection layers (sensor monitoring system inputted in an impermeable layer), and pedological and geological characteristics (taking the sample from shallow and deep drilling pit) [69].

There are very few scientific articles that report the monitoring results of the parameters indicated above. This fact shows the need to apply environmental regulations and make the results public; Table 1 below shows a summary of three case studies.

As can be seen, none of the three cases analyzed are all of the necessary parameters reported; therefore, this information has highlighted the importance of monitoring landfill post-closure can be duplicated at any landfill.

4.1.1.4. Composting. One of the main components of MSW is organic matter from foodstuffs. These wastes represent an environmental challenge due to the production of unpleasant odors, leachates (soil and water contamination), and greenhouse gas (GHG) emissions. Composting is a technique in which organic matter is transformed under necessary conditions of temperature, carbon to nitrogen (C: N) ratio, moisture, and aeration into nutrient-rich compost, which can be used to improve soil fertility and as plant food.

There are two types of composting called traditional and worm composting. The main characteristics are shown in Table 2.

Although composting is an environmentally friendly technology that allows us to obtain a product that benefits the agro-industrial industry, there are also many opportunities to improve the process, mainly in terms of emissions generated during the process, such as leachate, odors, and dust (CH_4, NH_3, N_2O, and volatile organic carbons) [73].

4.1.2. Thermal methods

4.1.2.1. Incineration. Incineration is a process in which waste in the presence of oxygen is subjected to a high temperature of between 850 and 1100 °C, reducing the waste's weight and volume significantly while taking advantage of the heat and energy generated. The most common incinerators are grate, fluidized bed, or rotary; besides excess air, the most critical parameters to obtain the best performance of the different incineration technologies are related to optimizing mass and energy transfer processes. The parameters used as external indicators of the quality of the process are the minimum combustion temperature and the residence time at this minimum temperature. A third parameter is a turbulence to facilitate the proper interaction between particles. The energy efficiency of this technology is for the generation of heat (80%), steam (20–30%), and electricity (20%) [55]. Incineration has numerous benefits; however, it is an expensive technology and can produce pollutants such as acid gases, carcinogenic dioxins, nitrogen oxides (NO_x),

Table 2
Main differences between the different types of composting.

Traditional Composting	Worm Composting
Requires minimum space of 0.4 m^3	It does not depend on the size
Outdoor only	Indoor or outdoor
Reaches high temperature to eliminate seeds and pathogens (65–72 °C)	Do not reach high temperatures
Some physical work is required	Minimum physical work demand
Requires a balance between C and N	It does not require a balance between C and N
Different types of bacteria are involved in the process	Only worms
The finished product is a soil amendment	The finished product is a soil amendment and mild fertilizer

Table 1
Parameters monitored at the closed landfill site.

Landfill	CH_4	CO_2	H_2S	Temperature °C	Reference
Shangai, China (naked cover soil)	Between 59.4 ± 14.4 to 65.7 ± 6.5%	Between 33.6 ± 4.1 to 35.5 ± 3.9 %	Between 12.7 and 1164.8 ppm	Between 14.6 and 19.2 °C	[70]
Shangai, China (vegetated cover soil)	Between 19.6 ± 5.0 to 46.3 ± 18.1%	Between 17.3 ± 1.8 to 27.8 ± 6.8%	Between 0 and 16 ppm	Between 13.5 and 17.0 °C	[70]
Taman Beringin (Malaysia)	Between 550,000 to 850,000 ppm	Between 400,000 to 620,000 ppm	–	between 32 and 42 °C	[71]
Halton (Ontario, Canadá)	Between 0.1 and 63 ppm	–	–	–	[72]

sulfur oxides (SOx), and ashes that may contain heavy metals. It is crucial to address these areas of opportunity to take advantage of the benefits of incineration under safe operating conditions for people and the environment.

4.1.2.2. Pyrolysis. Pyrolysis is a WtE technology that consists of thermally degrading waste without oxygen. The only oxygen present is that contained in the waste to be treated. This method works at temperatures between 300 °C and 800 °C. There are two common types of pyrolysis methods: conventional or slow (500 °C, heating rate 0.5 °C/s) and flash (765 °C, heating rate 100 °C/s) [74].

The result of the process is a gas whose elemental composition consists of CO, CO_2, H_2, and CH_4 [75]. This gas is very similar to the synthesis gas obtained in gasification. Still, there is a more significant presence of tars, waxes, etc., to the detriment of gases because pyrolysis works at lower temperatures than gasification. A liquid residue is also obtained as a product, composed mainly of long-chain hydrocarbons such as tars, oils, phenols, and waxes formed when condensing at room temperature. A solid residue comprises all non-combustible materials. The liquid and gaseous residues can be utilized by combustion through a steam cycle to produce electrical energy. The solid residue can be used as fuel in other industrial processes. The advantages of this technology are the reduction of weight and volume of the MSW, the gases generated have a low concentration of pollutants, and the heavy metals are trapped in very stable solids; however, it is a costly and relatively slow process, and although the concentration of pollutants is low, the generation of chlorinated, nitrogenous and sulfur compounds is not eliminated. Finally, solid waste as slag is greater than the volume of ashes obtained by incineration.

4.1.2.3. Gasification. Gasification is an attractive WtE alternative, which is carried out a thermochemical conversion process of High-carbon MSW into a gaseous product called synthetic gas (syngas) at high temperatures with the aid of a gasification agent. Syngas composition varies with the feedstock and gasification condition process, and it generally is composed of 30–60% CO, 25–30% H_2, 0–5% CH_4, 5–15% CO_2, as well as smaller amounts of water vapor, sulfur compounds, H_2S, NH_3, and other trace contaminants.

The gasification process consists of several stages, (1) moisture is removed from the waste by drying, and then (2) devolatilization, through pyrolysis, the volatile components of wastes are released. Vapors produced in this stage undergo thermal cracking to gas and char, (3) finally, the carbon remaining after pyrolysis is reacted with the gasifying agent, either air (direct gasification), oxygen (Pure oxygen gasification), or steam (Indirect gasification) at temperatures between 760 and 1200 °C [76]. Gasification with air results in a fuel gas rich in nitrogen but with low in heating power (BTU), while using pure oxygen results in a mixture of CO and hydrogen and practically no nitrogen; on the other hand, if steam is used, the result will be a syngas rich in hydrogen and CO_2. Although this technology has several advantages, such as obtaining syngas that can be used for various purposes (electricity production, use as fuel, production of a wide range of chemicals), the ease of handling the products, and the ability to regulate the compounds obtained, minimizing or eliminating the formation of dangerous compounds (prior selection of materials entering the process and of the gasifier agent), it also presents challenges to be improved, mainly in making its operation less complex, scaling up to higher capacities or implementing it in such a way that it is flexible and modular.

4.1.3. Chemical & mechanical methods

4.1.3.1. Esterification. The main product of esterification and transesterification reactions is biodiesel, a liquid fuel obtained from a feedstock of different origins: first-generation oils (edible oils), second-generation oils (non-edible oils, used cooking oils (WCO), and animal fats), and third-generation oils (algal biomass) [77].

Biodiesel production can be obtained using homogeneous, heterogeneous, and enzyme catalysts. In any process, the reaction is the same (oil + alcohol → biodiesel + glycerin). The difference is the type of catalytic process to be used. Homogeneous catalysts are used at the industrial level due to their higher reaction rate and yield. However, they have disadvantages that require additional neutralization and purification processes and the generation of wastewater, and the impossibility of recovering the catalyst. On the other hand, heterogeneous catalysts can be easily separated from the products and reused in several cycles. While enzymatic catalysts are emerging due to low-quality feed oils and animal fats [78].

4.1.3.2. Mechanical biological treatment (MBT). A mechanical biological treatment system consists of two processes, one hand waste sorting and the other hand biological treatment, such as anaerobic digestion and composting. The mechanical stage employs crushers, shredders, bag splitting, oversize picking, or hammer/ball mill to separate the disturbing parts, recyclables, and high caloric value fraction. The process continues with the biological stage to obtain the final products of both stages: recyclable materials, refuse-derived fuel (RDF), biogas, and compost (Fig. 3).

It is an ideal technology for countries with low recycling levels. It has been shown that using MBT before landfill disposal allows the recovery of inorganic materials and reduces mass and environmental impact by up to 30% [79]. However, MBT is neither a single technology nor a complete solution. It combines a wide range of processing techniques and operations tailored according to the composition of the waste to be treated.

A list of traditional WtE studies done to assess the influence of run-time parameters on the product yield can be seen in Table 3.

4.2. Non-conventional methods

4.2.1. Photo-biological process

One of the ways to generate clean fuels is through photobiological processes; biohydrogen can be obtained from water and organic matter in the presence of very particular microorganisms and multiple microorganisms which metabolize hydrogen, giving H_2 as the final product. Photobiological hydrogen production can take place through photofermentation or photolysis.

Photofermentation requires the presence of photosynthetic bacteria (e.g., *Rhodobacter sphaeroides, Rhodopseudomonas capsulate, Rhodopseudomonas palustris, and Rhodospirillum rubrum*) since their function is to take advantage of sunlight to convert organic matter into biomass while releasing CO_2 and H_2 in anaerobic conditions. The common photofermentation reaction can be described as follows [98]:

$C_6H_{12}O_6 \rightarrow 6\ CO_2 + 12\ H_2$ (in presence of photosynthetic bacteria).

When nitrogen-deficient conditions are present, one option is to use purple non-sulfur bacteria (PNS) because they can produce hydrogen as a by-product of nitrogenase activity, which is facilitated by sunlight and small organic molecules that serve as substrates. Anoxygenic phototrophs perform electron transport and generate the proton motive force that leads to ATP production using sunlight.

The most important factors to obtain the highest hydrogen production are intensity and wavelength concerning illumination. On the part of the bacteria, suitable conditions (photofermentation broth with the substrate, inoculum, and medium) are required for their growth and impact on the bacteria gas generation. Photofermentation can be coupled with dark fermentation. The maximum percentage of hydrogen obtained (68%) has been reported in the literature [99], which positions this technology as promising for the future.

Photolysis is a process in which cyanobacteria and blue-green algae containing chlorophyll and other pigments operate on a principle similar to photosynthesis in plants (Fig. 4). There are two types of

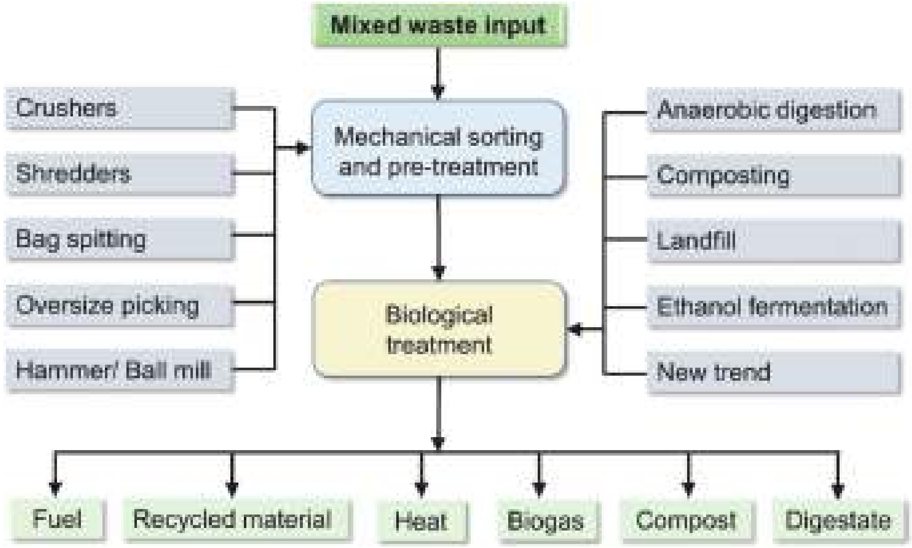

Fig. 3. Main steps involved during mechanical biological treatment (MBT).

photolysis, direct and indirect [98].

Direct photolysis involves photosynthesis, in which microalgae break down water into hydrogen and oxygen as indicated by the following reaction:

$2H_2O$ + solar energy + microalgae → $2H_2 + O_2$.

While in indirect photolysis, reduced substrates (i.e., carbohydrates, such as starch in microalgae or glycogen in cyanobacteria) are accumulated during the photosynthetic O_2 production and CO_2 fixation stage and then used in the second stage of carbon fermentation giving rise to H_2 production under anaerobic conditions:

$12H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$.

$C_6H_{12}O_6 + 12H_2O \rightarrow 12H_2 + 6CO_2$.

4.2.2. Dark fermentation

Dark fermentation is an alternative technology to produce bio-hydrogen from organic waste. It is a promising process since it works at room temperature and pressure and with bacterial consortia, which considerably reduces the cost of production. This process is carried out under anaerobic and dark conditions in bacteria like *Bacillus* sp.*, Clostridium* sp.*, Klebsiella* sp.*, and Enterobacter* sp., pure or mixed (consortia) [100]. The stages carried out are similar to those described for the anaerobic digestion (the organic feedstock will be breakdown by hydrolysis into more simple molecules and finally converted into a mixture of organic acids with low molecular weight and alcohols, mainly acetic and ethanol, both of commercial interest), the difference being that the hydrogen (H_2) generated during the first stages of anaerobic digestion is recovered, preventing it from being consumed by the methanogenic bacteria. The most critical parameters to control are the pH of the medium, quantity, and composition of organic matter, inoculum type, and ratio concerning the feed, temperature, and stirring speed.

4.2.3. Microbial fuel cell (MFC)

Microbial fuel cells (MFCs) are bio-reactors that use microorganisms (called exoelectrogens) to convert the chemical energy contained in organic matter into electrical energy. These microorganisms feed on organic waste and generate electrons that are transferred to an electrode as a product of their metabolic activity. The organic matter (domestic waste, animal waste, and wasted sludge) that serves as feed is degraded so that we can use these cells for two purposes, generation of clean energy and bioremediation of organic matter.

There are different configurations for MECs (double-chamber, single-chamber, stacked, and up-flow) [101] he most common is known as a double-chamber. In this configuration, the bio-reactor consists of two chambers containing an electrode. The first includes the anode (anaerobic process), which includes microorganisms that will act as a catalyst. This chamber is filled with feed consisting of organic matter. The microorganisms will digest the waste releasing electrons. A proton exchange membrane (PEM) is placed. The protons generated in the anode compartment will diffuse through the membrane to the cathode chamber (aerobic process), where it combines with oxygen to produce water. Finally, the electrical energy generated is extracted through an external circuit connecting the two electrodes (Fig. 5).

On the one hand, research has focused on optimizing the most critical variables of the process, such as the materials of the electrodes, chambers, and proton exchange membrane, as well as the use of catalysts and the adequate selection of the bacterial consortium according to the load to be treated, and by the other, the use of hybrid systems that combine dark fermentation and microbial fuel cells to produce both electricity and hydrogen: this technology can undoubtedly become relevant within WtE technologies [102].

4.2.4. Microbial electrolysis cell (MEC)

Microbial electrolysis cells (MEC) are a green technology that combines the operating principles of an anaerobic biomass reactor and an electrochemical cell for water electrolysis. The MEC has a similar construction to the MFC, i.e., two electrodes (anode and cathode) separated by an ion-exchange membrane. Unlike the MFC, this new generation of cells requires external energy (0.5–1.23 V) to carry out the chambers' reactions. On the one hand, in the anode chamber, the oxidation of the organic matter present in the waste will be carried out thanks to the metabolic process of the microorganisms present, and on the other hand, in the cathode chamber, the reduction of protons to produce hydrogen and also other value-added products. Research on MEC accepts above 90% of H_2. A yield of 87.73% was reported using a cathode-on-top single-chamber MEC [103]. Grid systems resulting from the combination of different WtE technologies can also be tested to produce energy and, at the same time, degrade contaminants [103].

A list of relatively recent WtE studies done to assess the influence of runtime parameters on the product yield can be observed in Table 4.

While most unconventional methods are promising technologies for generating H_2, an environmentally friendly fuel, several problems hinder their implementation at the industrial level. To implement some emerging technologies (photofermentation, dark fermentation, photolysis, microbial fuel cells, and microbial electrolysis cells), optimal H_2 production at a feasible cost is required. Some challenges to be overcome for industrial scale-up are discussed below [109-111].

Table 3
List of traditional WtE studies done to assess the influence of runtime parameters on the product yield.

Feedstock	Pretreatment	Technology	Catalyst	Microwave Power	Temperature (°C)	Residence time	Yield (untreated)	Yield (treated)	Treatment condition	Remarks on product quality	Reference
Wheat straw with cattle manure	Physical: cavitation	Anaerobic Digestion	–	–	–	–	193 mL/g VS	249 mL/g VS	Full-scale AD, mesophilic, ultrasonic cavitation	CH_4	[80]
Sida hermaphrodita wheat straw	Hydrothermal: hot water, 150° C, 15 min	Anaerobic Digestion	–	–	35 °C	–	370.3 mL/g VS	575 mL/g VS	Lab-scale batch AD	CH_4	[81]
Rice straw	Chemical: ionic liquid (NMMO, 120° C, 3 h)	Anaerobic Digestion	–	–	37 °C	–	206 mL/g VS	374 mL/g VS	Lab-scale	CH_4	[82]
Pulp and paper sludge	Biological: Microbial consortium OEM1	Anaerobic Digestion	–	–	–	–	179 mL/g VS	429.19 mL/g VS	Lab-scale CSTR in mesophilic	CH_4	[83]
Food waste	–	Anaerobic Digestion	–	–	35 °C	25 days	–	437 mL/g VS	2.4 g VSFW/L/day, mixing 2 mins/hr	CH_4	[84]
Food waste	Hydrothermal: 100–160 °C	Ethanol fermentation and anaerobic digestion	–		–	–		191.10 g ethanol/Kg of dry MSW and 156 L CH_4/Kg of MSW	Cellulosic + starch hydrolyzates + 2 g/L yeast extract for ethanol production and 37 °C for 50 days for AD.	C_2H_5OH CH_4	[85]
Starchy biowastes	–	Ethanol fermentation	–	–	30 ± 1 °C	72 h	–	167.80 ± 0.49 g/kg of biowaste	BioFlo/CelliGen 115 fermenter (5 L)	C_2H_5OH	[86]
MSW 6124 m^3/day	–	Landfill	–	–	–	–	–	70 m^3/t (44% efficiency)	The capacity of about 120,000 tons of MSW. The total area of 53 ha is divided into four cells.	C_2H_5OH CH_4	[72]
MSW	–	Landfill	–	–	–	–	–	81 m^3/Mg (57%, 0.355 $year^{-1}$)	8 cells with a volume of 46,180 m^3 /cell and a receiving capacity of 705,271 t/cell	CH_4	[87]
MSW	–	Incineration	–	–	1100 °C	–	–	53.72 MW for electricity and 99.4 MW for heat	2000 ton MSW/day; 8227.1 kJ/kg for MSW	Electricity and heat	[88]
MSW and sewage sludge	–	Incineration	–	–	–	–	–	30 MW	Circulating fluidized-bed; 70 t/d × 2	Electricity	[89]
MSW and MSW/NHIW	–	Incineration	–	–	–	–	–	Operational efficiency 0.314–0.623 kW-h/kg	Incineration type: Martin (Germany), Takuma (Japan), and DBA (Germany) with 3 furnaces, and Martin (Germany) with 4 furnace	Electricity	[90]
Rice husk (agricultural waste)	–	Microwave pyrolysis	–	500 W	400–700 °C	18 min	–	68% biochar, 25.46 MJ/kg, fixed carbon content 52.2%, and surface area 190 m^2/g	Microwave oven reactor, operating at a frequency of 2.45 GHz, N_2 flow rate 0.2 L/min	Biochar	[91]
Plastic wastes	–	Continuous microwave-assisted pyrolysis	ZSM-5	9 kW	620 °C	15–90 s	.	The liquid yield of 48.9%, the energy efficiency of 89.6%, 6.1 MJ electrical energy	Continuous down-draft microwave-assisted pyrolysis system, plastic feedstock 10 kg/h, 200 g of ZSM-5	Gas (H_2, CH_4, C2-C4 alkanes and alkenes), liquid (aromatic, n-	[92]

(*continued on next page*)

Table 3 (*continued*)

Feedstock	Pretreatment	Technology	Catalyst	Microwave Power	Temperature (°C)	Residence time	Yield (untreated)	Yield (treated)	Treatment condition	Remarks on product quality	Reference
										alkene, and C5-C12), and wax.	
MSW	–	Pyrolysis and catalytic cracking	–	–	900 °C	–	–	Syngas 80 vol% CO and H_2 with a heating value of 16 MJ/Nm^3	Pyrolysis (stainless steel fixed-bed reactor, N_2 300 mL/min) + cracking (tubular reactor)	Syngas and char	[93]
MSW	–	Gasification	–	–	above 1200 ∘C	8 h	–	Cold gas efficiency is 89.31% at an equivalence ratio of 0.35	Downdraft gasifier, air flow rates 140–150 kg/h, 0.035 bar, equivalence ratio of 0.35		[94]
Pellets and fluffy MSW	–	Gasification	–	–	1200 °C and above	8 h	–	250 m3 /hr which corresponds to 50% wood + 50% MSW, maximum gas energy content value 1250 kcal/Nm3	Downdraft gasifier, feedstock rate 100 kg/h, equivalence ratio of 0.4, air flow rate 147 to 149 m3/hr	Syngas (H_2, N_2, CO, CO_2, CH_4, moisture)	[95]
MSW Capacity in 2017: 42,000 tons of non-recycled waste plus 37,989 tons of green waste	–	Landfill and Municipal Green Waste Gasification	–	–	–	–	–	Electrical efficiency of 16.22%,	All Power Labs PP30 fixed bed gasifier	CH_4, compost, Syngas (H_2, N_2, CO, CO_2, CH_4), biochar, heat, and electricity	[96]
MSW 100 tons per day	–	Mechanical Biological Treatment	–	–	48–52 °C	15 days	–	11.90% recyclables, 33% RDF, 5% compost of total waste received, and 0.435 MWh/day electricity. The biogas and methane yields were 0.535 and 0.350 m^3 /kg VS	It is designed to recover recyclables from the waste, segregate the waste into dry and wet fractions using organic extrusion followed by bio-methanation of the wet fraction, generation of electricity, and compost	CH_4, RDF, compost, and recyclables	[97]

MSW: municipal solid waste; NHIW: non-hazardous industrial waste.

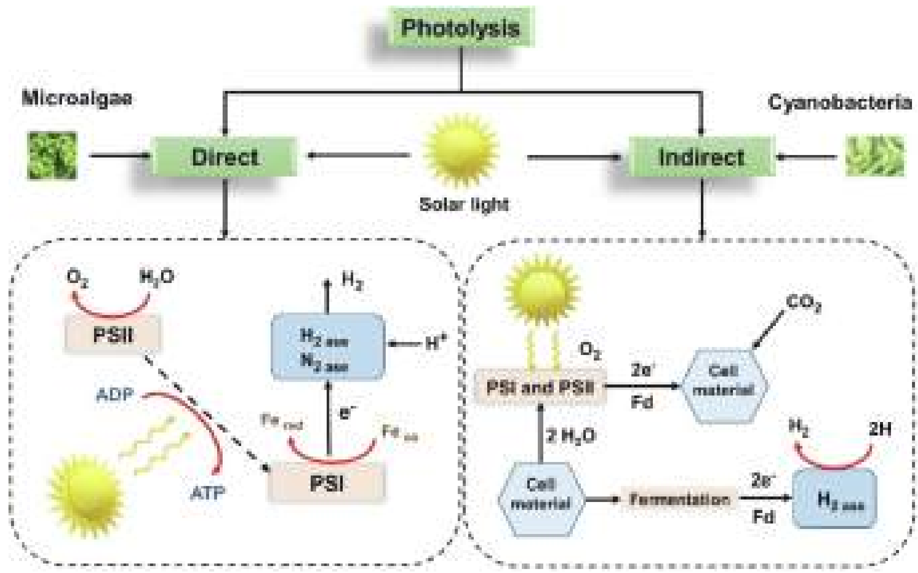

Fig. 4. Process flow schematics: showing (a) Direct and (b) indirect photolysis.

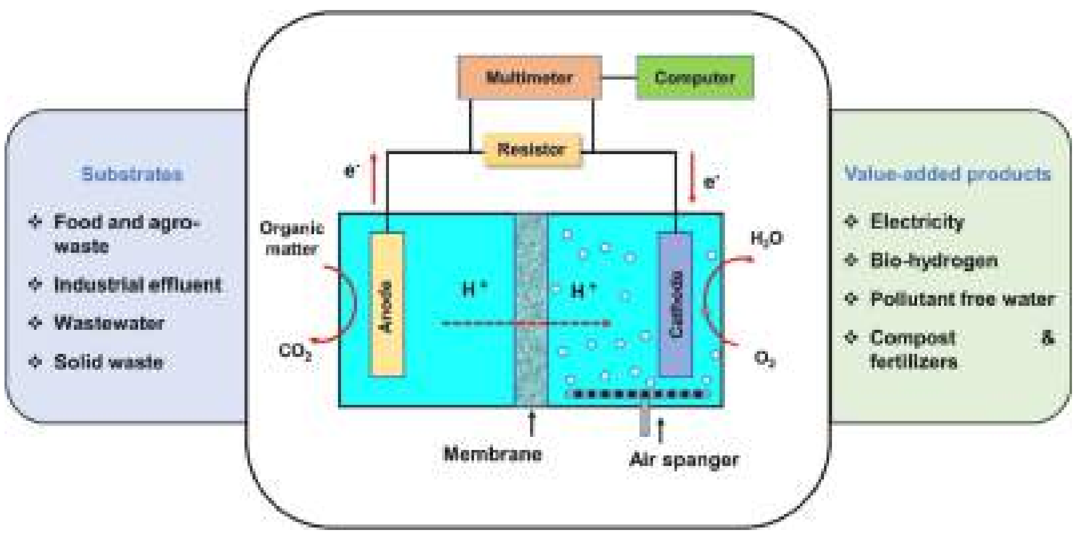

Fig. 5. Schematic representation of the constitution of a microbial fuel cell.

- The variability of the composition and source type of organic waste.
- In practice, there are many research studies on batch processes, while a continuous operation is desirable for the industrial level.
- Those processes that require illumination, such as photo-fermentation and photolysis, will be affected by the color of the residues; dark colors will inhibit light absorption, making pretreatment necessary.
- In the case of microbial fuel cells and microbial electrolysis cells, it lies in preventing decreased efficiency as reactor volume expands, long-term stability of construction materials (cell structure), and cost of components (electrodes, membranes, catalyst, current collector, etc.) complex modular design, etc.

Some of the proposals to solve these challenges are as follows:

- Conduct further R&D studies to determine the effect of the most critical parameters for each process.
- Optimize the design of the reactors once the system is well known, and even use a combination of technologies such as photofermentation with dark fermentation or dark fermentation and microbial electrolysis cell.
- Use a combination of green microalgae and photosynthetic bacteria.
- Employ genetic engineering to manipulate the metabolic pathways of the photofermentation and photolysis processes to increase hydrogen generation.

5. Case studies of a few countries – India, Brazil, and New Zealand

5.1. India

India generated 62 million tons of MSW in 2015; according to models, the estimated generation in 2021 will be 71.15 and 160.96 Mt/year for 2041. The efficiency of the collection system ranges between 70% and 95% in large cities, while in several smaller cities, it is below 50%. MSW composition is approximately 40%–60% organic matter, 30%–50% inert, and 10%–30% recyclable [112]. Of the waste generated, approximately 82% is collected, of which 5% is recycled, 18% is composted, and 77% is destined for open dumps [113].

Table 4
List of relatively recent WtE studies done to assess the influence of runtime parameters on the product yield.

Feedstock	Pretreatment	Technology	Catalyst	Temperature (°C)	Residence time	Yield (untreated)	Yield (treated)	Treatment condition	Remarks on product quality	Reference
Hydrolyzed corn stover	–	Dark and photo fermentation	–	35 °C dark fermentation, 30 °C photofermentation	16 h	–	87.8 ± 3.8 m^3/d with 68% H_2 content, contributed by dark unit at 7.5 m^3 –H_2/m^3 -d and by photo unit at 4.7 m^3 /m^3-d	3 m^3 for dark and 8 m^3 for photo compartments. A combination of solar energy and a light-emitting diode was used for photo fermentation.	H_2	[99]
Cornstalk hydrolysate	Chemical: HCl	Photo fermentation	–	33 °C	50 h	3.64 ± 0.18 mol-H_2/g-cornstalk with wild type strain	40.07 ± 1.70 mmol-H_2/(h·g-cornstalk) with mutant strain *Rhodobacter capsulatus* MX01. 10.6% conversion efficiency	350 glass bioreactors with 200 mL working volume. Light intensity (5000 lx and 7000 lx).	H_2	[104]
Corn stover	–	Photofermentation	SnO_2	35 °C	–	–	345 mL	Photosynthetic mixed consortium HAU-M1, pH 6.5, and Illumination of 192 W/m^2 (300 W)	H_2	[105]
Macroalgae *Saccharina japonica*	–	Dark fermentation and microbial electrolysis cell	–	36.6 °C	–	–	492.3 ± 5,1 mL/g-TS	A working volume of 250 mL was used in a single chamber-type MEC. A graphite fiber brush twisted between two titanium wires was used as the anode. A carbon cloth comprising a Pt catalyst (60% Pt/C) was used as the cathode	H_2	[106]
Waste sludge lysate	–	Microbial electrolysis cell	–	–	5 days	–	22 ± 7.3 mL at 1.0 V Efficiency current conversion 17.68 ± 6. 21%	A cylindrical chamber made of the polycarbonate of 28 mL volume. Anode of graphite brush and cathode of carbon cloth	H_2	[107]
Food waste	–	Microbial electrolysis cell	–	30 °C	38 days	–	873 mL H_2/g COD	Cells made of acrylic, 450 mL volume, an anode of graphite felt, a cathode of nickel, and an anion exchange membrane (AEM; AMI-7001, Membranes International, Glen Rock, NJ)	H_2	[108]

The Government of India has taken an essential step by contemplating the WtE policy under the Municipal Solid Waste Management (MSWM) Rules. The Ministry of New and Renewable Energy (MNRE), 2014, has reported that 1460 MW of energy could be obtained from municipal solid waste. Consequently, co-processing and cogeneration technologies are essential in India's integrated solid waste management (ISWM) [114].

The first MBT-based WtE plant was recently commissioned in Saligao, North Goa, with a capacity to treat 100 tons/day of municipal solid waste and a generation of 0.8–1.0 MWh of energy. This plant is designed to recover recyclable materials from the waste and segregate them into dry (RDF for energy recovery) and wet fractions by organic extrusion, followed by bio-methanation of the wet part to generate electricity and compost [97].

Tyagi, VK et al. evaluated the energy, environmental and techno-economic feasibility of the MBT system. The results indicate that from the total treated waste, they obtained: 11.90% recyclable materials, 33% rejected derived fuel (RDF), 5% compost, 70 m^3/day of recyclable water, and 0.435 MWh/day of electricity. Biogas production was 5000 m^3/day with 65% CH_4 content. From an economic point of view, this generation can earn $995 per day/148 tons of waste processed ($6.72/ton). Overall, the study revealed that it is ecologically, economically viable, and socially acceptable [97].

5.2. Brazil

Brazil generates 217 thousand tons of MSW/day; the efficiency collection is about 92.01% [115]. Moreover, the composition of waste varies depending on the city or municipality where it is generated, for example, in the city of São Paulo are made up of organic waste (53%), paper (11%); plastics (16%), metals (2%), and miscellaneous waste (2–16%); while in the municipal district of Santo André were reported the following composition: organic matter (44.3%), paper/cardboard/tetrapak (9.9%), plastics (13.8%), glass/metal and other inert (11.3%), sanitary waste (11.9%), and textile (8.8%) [116,117].Waste management is almost entirely made by the government (94%), and the participation of private companies is limited; however, it seems that this situation is about to change [115].

Derived from its active role in the international arena, Brazil has incorporated environmental concerns into the Brazilian legal system. Thus, in 2010, the National Solid Waste Policy Law (NSWP) included energy recovery from waste as one of the options for the treatment and disposal of municipal solid waste. This has generated interest in the study, development, and implementation of WtE technologies. This law is based on the "polluter pays" principle and is applicable to both individuals and legal entities, which are either directly or indirectly responsible for the generation of solid waste. As a result, most of the responsibility for paying for or providing waste management falls on its producers. This national policy also incentivizes the study, development, and implementation of WtE technologies for recovering energy from municipal solid waste. Burning landfill biogas in internal combustion engines and incineration of solid waste are proposed options, provided that their technical and environmental feasibility is guaranteed [117].

Brizi, F., et al. analyzed a compact cogeneration system comparing the use of natural gas and biogas. Cogeneration is based on the simultaneous production of electric power and heat from the burning of a single fuel. They found that there is more hot water production using natural gas as fuel than using biogas; while using biogas produces more hot water in the exhaust gases and, therefore, the production of cold water is higher. If a payback period of 5 years is considered, it is more economical to use biogas. However, in order to have a better picture it is important to consider the particular application before defining the type of fuel [118].

Gutiérrez-Gómez, A. C., et al. evaluated the potential for energy recovery from MSW for direct combustion and energy recovery. For this purpose, they performed the thermochemical characterization of mixed waste contaminated with organic fractions (wet MSR) from five different regions of Brazil. The heating values estimated for the North, Midwest, and South regions are between air preheating zones and auxiliary fuel, except for the Southeast region, whose calorific value is considered medium–high (8.99 MJ/kg). However, the waste collected from the Northeast region presents the lowest LHVwb of the Brazilian waste, well below the recommended values for waste combustion ($\geq$6 MJ/kg) [119].

On the other hand, the authors evaluated the implementation of WtE technologies using two different systems, a hybrid cycle with a gas turbine burning landfill biogas and an incinerator burning solid waste (with 3 different configurations) and a solid waste gasification system to burn syngas in gas turbines (IGCC) [120].

The comparative analysis of the different configurations indicates that the integrated gasification combined cycle (IGCC) system is technically more attractive than the hybrid system in its three configurations because it presents the highest power and thermal efficiency values. Furthermore, in a preliminary analysis, from the economic point of view, the cost of electricity of the IGCC turned out to be lower than that of the hybrid cycle, with values in the range of 32–53 USD/MWh for the plant operating 6500 h/year and this value decreases 24–39 USD/MWh for the plant operating 8760 h/year.

We can conclude that the main achievement in Brazil is that they have an established policy that encourages the use of technologies for the generation of energy from municipal solid waste. However, the production of energy through these methods still requires improvement. The first WtE plant is currently under development in Barueri in Sao Paulo, with a capacity to treat 825 tons/day of municipal solid waste and electrical power of 20 MW [115] there is still no information on its operation.

5.3. New Zealand

In New Zealand, waste management is a particularly concerning problem because it ranks in the top 10 globally in MSW generation per capita, ranking it the most wasteful country in the developed world. In 2018, New Zealand generated approximately 781 kg of solid waste per capita per year, significantly higher than the OECD total of approximately 525 kg of waste per capita per year. Waste composition of landfills (2011–2017) reported: organic matter 30.4%, timber 14.1%, plastic 12.1%, paper 9.0%, nappies and sanitary 6.3%, textiles 5.4%, rubber 0.9%, rubble and concrete 10.0%, potential hazardous 4.4%, glass 3.3% and 3.1% of metal, of which 94% of waste treated in landfills. It is estimated that 78.2% of MSW can be used for different WtE plants [121].

Currently, the primary waste management strategy adopted by the New Zealand government is to reduce, reuse and recycle. However, most of the non-recyclable and non-reusable waste ends up in landfills. Although landfills may be the most economical solution in the short term, their environmental impact and sustainability are a problem in the long term [122].

Although waste generation, composition, collection-separation systems, treatment technologies, economics, policies, and infrastructure are very different from one country to another, there are some common challenges. One of them is the separation of waste at source and an efficient collection system, which mainly affects developing countries, as there is a lack of adequate strategies and policies. In all three cases, there is the problem of implementing appropriate WtE technology and skilled labor and optimizing the relationship between the different sectors of government, academia, and society.

6. Road maps for achieving WtE for developing countries

Renewable energy, including WtE plant construction, is becoming more popular in a few nations. At this point, it's a significant step in the right direction and might have a substantial impact on MSWM. The community must put up a large amount of money toward constructing a WtE facility.

Renewable energy, including WtE plant construction, is becoming more popular in a few nations. At this point, it's a significant step in the right direction and might have a substantial impact on MSWM. The community must put up a large amount of money toward constructing a WtE facility. It is essential to have a well-defined plan for eventually building a WtE plant to begin such a massive undertaking [114]. Phases of the proposed project include a feasibility study, a design and construction phase, and an operational phase. The first stage in building a WtE plant is a feasibility study. At this point, the project's scope and goals should be clear [121]. WtE facility development's economic, technical, environmental, social, and legal feasibility is under one umbrella. Economic feasibility comprises a detailed cash flow analysis of the project's design and construction costs, yearly operating and maintenance costs, and annual income. International financial institutions, NGOs, nations with recent WtE experience, global renewable energy consultants and developers, and published literature are all possible data sources on costs and revenues for WtE programs. Financial analysis approaches, such as payback time, present value, and internal rate of return will be used for different scenarios. There should be a thorough examination of the initiatives' financial needs and possible earnings [123].

This technical evaluation was conducted to evaluate the current status of WtE technology and forecast future MSW amounts and compositions. The most suitable and efficient WtE technology will be identified by comparing many alternative WtE technologies in terms of their pros and shortcomings. Only a conceptual design but comprehensive enough to provide a reasonable cost estimate and project timeline will be used for this project. To maximize energy yield, heat/steam generation and cogeneration potential (if heat and electricity can be generated simultaneously) will be assessed [124].

In terms of technical feasibility, this entails determining the amount of trash recycled, determining if the waste is suitable for thermal treatment, determining which technology is most efficient, and determining how long the facility will be operational. The chosen WtE technology will be used to create an environmental evaluation. Various ecological baseline data are gathered in this process, including information on the surrounding area's geography and ecology. There should be an assessment of the potential for contamination of soils, air, groundwater, surface water, and noise. We need to develop a list of potential solutions and test them out. Determine the cost and time for mitigation measures and include them in the project cost and schedule [121].

It is essential to do a social assessment to assess the social context in which one aspect is successful. MSW recycling and the plant's construction will proceed more quickly if the public is on board with the project [124]. If feasible, materials should be recycled, conventional and non-conventional WtE technologies should be used, and landfills should be minimized. Composting and anaerobic digestion are used for organic waste, whereas gasification and hydrothermal processing are used for inorganic waste that cannot be recycled. More minor, decentralized WtE facilities may also be an option for a steady supply of MSW. Solid waste can be carefully handled, and an enormous amount of MSW will be dumped since the landfill option is no longer viable. Non-conventional WtE processing methods may be made more affordable in New Zealand by using plant facilities that produce valuable by-products such as pyrolysis oil, synthesis gas, and organic acids. Fuels, chemical compounds, and hydrogen are examples of high-value end products. Increasing plant capacity, using by-products such as vitrified slag in plasma gasification, employing lean manufacturing methods methodology, and integrating energy to minimize energy costs are other cost-cutting measures that may be used. Many feasibility studies are needed to examine the impact of crucial process parameters and design configurations on the yield and economy of these processes [121] or efficient process design, optimization, critical decision-making, and improving technological readiness levels. These studies are vital before their implementations at industrial size, and such basic investigations must be undertaken via industry-academia cooperation in the laboratory and pilot scales. It is also important to cooperate with a wide range of stakeholders, including local government, industry, and investment corporations, to ensure that the community and customers accept a proposed WtE system. For instance, the circular economy and WtE processing in New Zealand may benefit from integrating non-conventional and conventional technology.

7. WtE challenges and prospects

There has been a global concern regarding MSW due to the rapidly increasing amount of waste, environmental pollution, social inclusion, economic sustainability, and flexible environmental rules regarding MSW discharge [125,126]. A primary concern is its high organic content, and its proper disposal has become a vital issue. It may be possible to use integrated technologies to produce large-scale biomass, biopolymers, and energy from waste in the future. The WtE system and its integration with other technologies may be an effective way to treat MSW to achieve energy in the form of steam and electricity. In this context, an essential aspect of sustainability would be the development of a waste biorefinery utilizing the efficiency of recent developments in the recovery of resources from MSW.

The WtE scenarios provide a viable disposal solution for MSW and offer enormous economic and environmental benefits. A WtE supply chain gives a practical approach to generating energy and produces an integrated solution, e.g., reducing waste and GHG emissions, thereby serving economical and environmentally friendly profits [127]. Furthermore, WtE minimizes the MSW deposited at landfill sites, typically about 90% volume reduction and 80% mass reduction [128]. However, an NGO report reported that WtE does not contribute to the circular economy due to no residue left after burning in the incineration process [129]. According to the European Commission in the context of WtE incineration, "*WtE is a broad term that covers much more than waste incineration. It encompasses various waste treatment processes generating energy* (e.g.*, in the form of electricity/or heat or produce a waste-derived fuel), each of which has different environmental impacts and circular economy potential*". [130].

8. Conclusion

This paper aims to show the review of more than 130 published articles regarding the different separation- collection systems and WtE technologies and the analysis of the case of some countries. It was found from the available literature that a technology that simultaneously checks boxes from multiple standpoints such as economics, political, legal, and social, among others, is lacking due to the wide variability in waste composition and characteristics, socio-economic aspects, and geographical constraints. Therefore, it appears that currently it is not possible to completely utilize and repurpose the waste for both energy and material recovery. Hence, this effort sifts through existing conventional, non-conventional, and other WtE techniques to identify the benefits and limitation of each technology from the aforementioned standpoints and consolidates critical information for enhance MSW management in the future.

Implementing a WtE system requires a thorough review in which multi-criteria decision analysis methods can be used for decision making, and once this is established, optimizing the conditions of the entire system involving collection, transfer, and technology or combination of technologies (WtE and non-WtE). It is also essential to implement awareness and education programs for waste generators and municipal staff and have government support with incentives and policies that allow its implementation.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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