ARID ZONE JOURNAL OF ENGINEERING, TECHNOLOGY & ENVIRONMENT

AZOJETE September 2026. Vol.22(3):794-807

Published by the Faculty of Engineering, University of Maiduguri, Maiduguri, Nigeria.

Print ISSN: 1596-2490, Electronic ISSN: 2545-5818

https://doi.org/10.63958/AZOJETE/2026/22/03/020

www.azojete.com.ng

REVIEW ARTICLE

A COMPARATIVE REVIEW OF WASTE-TO-ENERGY TECHNOLOGIES FOR MUNICIPAL SOLID WASTE MANAGEMENT

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ARTICLE INFORMATION

Received: 17th June 2026
Revised: 3rd August 2026
Accepted: 5th August 2026

Keywords:
Anaerobic digestion
Gasification
Landfill
Incineration
Plasma gasification

ABSTRACT

Waste-to-energy (WtE) technologies are an important component of sustainable waste management systems and provide a practical solution to the increasing challenges of municipal solid waste generation and increasing energy demand. WtE technologies convert wastes to useful forms of energy, which help to reduce the volume of wastes, to mitigate greenhouse gases, and to recover resources. This paper presents a review and comparative assessment of five major WtE technologies: incineration, anaerobic digestion, landfill gas-to-energy, gasification, and plasma gasification, evaluated in terms of technical performance, environmental impact, economic viability, social acceptance, and technology maturity. The review shows that Incineration reduces waste volume by up to 90% and achieves electrical efficiencies of 20–30% (rising to 80–90% under combined heat and power) but generates ash residues requiring specialized disposal. Also, anaerobic digestion converts organic waste into biogas containing 50–70% methane, with electrical efficiencies of 35–40% (55–65% under CHP configurations) and having the lowest air emissions among those technologies reviewed. Similarly, landfill gas-to-energy captures gas that is roughly 40–60% methane and 30–50% CO_2, generated over 15–25 years, providing a low-cost route to recovering energy from waste already in place. Furthermore, Gasification converts waste into syngas with electrical efficiencies of 30–40% (60–80% as syngas energy) at 700–1,500 °C, offering greater feedstock flexibility than incineration. Plasma gasification operates above 3,000 °C, achieves waste volume reductions of up to 95%, and delivers the highest syngas energy efficiency reviewed (65–75%), though at the highest capital cost of the five technologies. The results show that although conventional technologies such as incineration and anaerobic digestion are still the most widely used due to their well-established and reliable nature, advanced options such as plasma gasification show a better environmental performance and feedstock versatility at higher costs. This paper provides useful knowledge to help inform decisions on appropriate WtE technologies to be selected for sustainable waste management, especially in rapidly urbanising regions.

1.0 Introduction

The rapid urbanisation, population growth and changing consumption pattern at global level has resulted in generation of huge amount of Municipal Solid Waste (MSW). Traditional waste disposal methods, namely open dumping and landfilling, are increasingly unsustainable due to land scarcity, environmental pollution and greenhouse gas emissions. Global energy demand is rising meanwhile, putting pressure on dwindling fossil fuel reserves and fanning worries about climate change. The combined challenges have necessitated the adoption of integrated waste management strategies that not only reduce waste volumes but recover value from waste streams.

Waste technology to energy is considered a prominent waste management method. The technologies are known for their dual advantage of waste reduction and energy recovery. Nowadays, these technologies are getting popular as a viable solution for the problems of growing waste production and energy usage (Peng *et al.* 2023). The most common waste to energy technologies include incineration, anaerobic digestion, pyrolysis, gasification, plasma gasification and others. WtE technologies can contribute to achieving the objectives of the circular economy. They can aid in diverting trash acumulated in the landfills and in decreasing the greenhouse gas emissions by converting municipal solid waste (MSW) and other types of waste to energy.

Waste-to-energy (WtE) technologies also play a significant role all over the world as they cooperate with recycling and composting practices so that unusable waste could be utilized instead of being discarded. In this context, it should be noted that waste-to-energy technologies often utilize thermal, biological or thermochemical methods of recovering energy from waste. Moreover, apart from energy production, these processes have the ability to minimize waste volume by up to 90% which saves space in the landfills and reduces the negative impact on the environment.

Interest in WtE systems is increasing, but no one technology is best fit for all waste management scenarios. Conventional technologies such as incineration and anaerobic digestion are relatively mature and widely implemented but face challenges related to emissions, residue management and feedstock limitations. In contrast, advanced technologies such as gasification and plasma gasification demonstrate improved environmental performance and higher potential for energy recovery, but often are constrained by high capital costs and technical complexity. Such trade-offs highlight the need for a holistic and comparative assessment of WtE technologies to support sound decision-making. The aim of the present study is to review and compare the major waste-to-energy technologies for the management of municipal solid waste.

2. Method

This paper provides an assessment of the major WtE technologies for MSW management by means of a literature based review and comparative analysis. Peer reviewed journal articles, technical reports, conference proceedings and publications were reviewed for current and relevant information on the performance and application of different WtE technologies. The selected WtE technologies were assessed against several criteria including: incineration, anaerobic digestion, landfill gas-to-energy, gasification and plasma gasification. These criteria include technical parameters (energy efficiency, operating conditions, flexibility in feedstock, and processing capacity), environmental parameters (air emissions, potential for reduction of greenhouse gases, management of residues and ash, and water use), economic parameters (capital costs, operation and maintenance costs, levelized cost of energy, and sources of income) and social parameters (public acceptance, health and safety concerns, and potential for jobs creation).

3. Overview of WtE Technologies

3.1 Incineration

Waste to energy (WtE) process also called as Combustion is the process of burning mixed MSW in excess air or oxygen at high temperatures, usually from 800 °C to 1200 °C. The process overview is shown in Figure 1. The first incinerators were primarily developed to cut down the mass and volume of waste going to landfill. But contemporary incinerators are designed to capture energy released by the burning process. The heat generated is used to produce steam, which can then be used to produce electricty. Indeed, the energy recovery plants of waste incineration operate similarly to the conventional power plants based on fossil fuels. These facilities typically consist of waste storage units, combustion or boiler chambers, steam turbines for power generation, and flue gas treatment systems for controlling emissions and environmental safety (Yakah, *et al.* 2023).

Incineration of MSW does not destroy the waste but it greatly reduces the amount that must be landfilled, typically by about 75% in weight and 90% in volume. The process, however, generates air pollution control (APC) residues that present considerable environmental issues, especially considering their potential to contaminate surface and groundwater. To reduce these risks, modern approaches require disposal of such residues in well-designed sanitary landfills with sophisticated leachate collection and treatment systems or in sealed underground mines, to prevent the leaching of heavy metals and chlorides (Beyene, *et al.* 2018).

However, incineration of the MSW is often a public controversy due to the concern of emission and environmental pollution. But it has two important roles in complex waste management systems. Generation of energy in the form of heat for the production of electricity or for heating. To reduce the volume of waste that has to be sent to a sanitary landfill. Therefore, incineration plants are usually located in places where land for sanitary landfills is scarce or where land for landfills is competing with other land use priorities such as urban development, agriculture or tourism (World Bank, 1999; Tong and Hu, 2022). Waste incineration is a high technology process and requires a huge amount of capital and operational expenditures (Imran, *et al.* 2024). Hence, the revenue from energy generation is important for the economic viability of these plants and the dynamics of the energy market is an important factor in the determination of their establishment. There are a number of incineration technologies currently in use. The most common and most reliable method is mass-burning incineration on a travelling grate. So, this method can be directly applied to the mixed municipal waste without any pre-treatment (Zakaria, *et al.* 2021). Fluidized-bed incineration is still largely experimental and not yet considered suitable for general application. Rotary kilns are also employed. The mass burning system has been upgraded over the years to meet the strict technical and environmental requirements and is the preferred option for MSW management in many developed areas (Kalogirou, 2024).

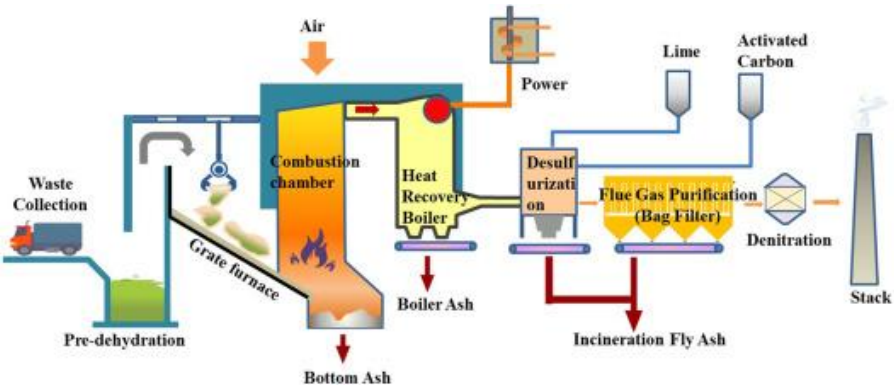

Figure 1: Overview of waste incineration process (Tong and Hu, 2022)

But there are numerous beneficial aspects and major disadvantages of rubbish incineration. Major worry is the air pollution from burning of waste items which emanate a variety of dangerous pollutants including particulate matter, nitrogen oxides and poisonous compounds such as dioxins and furans. Poor regulation of these pollutants can have substantial implications on environment and public health such as respiratory ailments, cardiovascular diseases and other long-term health concerns (Cai *et al.* 2023). The second important problem is what to dispose with the ash. Burning reduces the quantity and volume of rubbish substantially, but it doesn't make it go away.

This process produces bottom ash and fly ash, which are often rich in heavy metals and toxic compounds (Chen, *et al.* 2023). These residues have to be managed and disposed in special landfills with the containment and leachate control systems to avoid the contamination of the environment. This makes the whole waste management process more complicated and expensive.

Furthermore, incineration releases greenhouse gases. Waste combustion also provides for energy recovery and reduces the reliance on fossil fuels. But the process itself produces carbon dioxide and other gases that contribute to global warming. This is particularly problematic if the waste stream contains a high fraction of plastics or other carbon-rich materials from petroleum products (Kwon *et al.* 2023). Finally large scale use of incineration may hinder waste minimisation and recycling. The presence of incinerators and their financial attractiveness may reduce incentives for communities and industry to pursue waste minimisation or invest in recycling and composting programs (Yamamoto and Kinnaman, 2022). Thus too great a reliance on incineration can undermine the encouragement of sustainable waste management hierarchies which favour reduction, reuse and recycling over disposal.

3.2 Anaerobic Digestion

Anaerobic digestion (AD) is a biological waste-to-energy (WtE) process, whereby organic fractions of municipal solid waste (OFMSW) are decomposed under oxygen-free conditions, through the metabolic activity of microorganisms. The method produces biogas (mainly CH_4 and CO_2) and a nutrient-rich digestate which can be used as fertiliser or soil conditioner from biodegradable material (Tamilselvan and Selwynraj 2024). Figure 2. Schematic of the AD process simplified. The difference with thermal conversion (incineration, gasification etc.) is that AD takes place at moderate temperatures (mesophilic 35 °C, thermophilic 55 °C) and biological phases (hydrolysis, acidogenesis, acetogenesis, methanogenesis etc) (Olatunji *et al.* 2021).

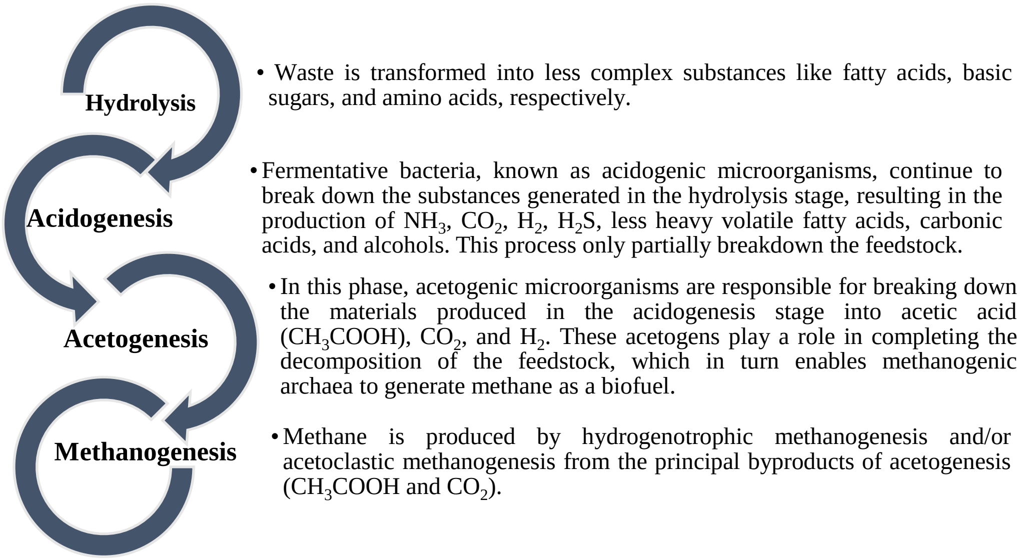

Figure 2: Primary stages in the process of anaerobic digestion

From Figure 2, the process begins with hydrolysis, where complex organic polymers such as carbohydrates, lipids, and proteins are broken down into simpler monomers like sugars, fatty acids, and amino acids. These products are then fermented during acidogenesis to form volatile fatty acids (VFAs), alcohols, hydrogen, and CO_2. In acetogenesis, further conversion of VFAs into acetic acid, CO2 and hydrogen occurs, which are finally metabolised by methanogenic archaea in the methanogenesis stage to produce biogas (Meenakshisundaram, *et al.* 2022). AD's efficiency depends on factors like temperature, pH (optimal range 6.8–7.4), carbon-to-nitrogen (C/N) ratio, substrate composition, and hydraulic retention time (Wang, *et al.* 2022).

AD systems are generally categorised into wet (total solids <15%) and dry (total solids 20–40%) digestion depending on the moisture content of the feedstock (Akinbomi, *et al.* 2022). Wet systems are more common in wastewater and food waste treatment while dry systems are particularly suited to solid waste streams like source separated organics and yard waste. The technology can be designed as single-stage or two-stage reactors. The latter offers improved process stability and methane yield by separating acidogenic and methanogenic phases.

The biogas from AD usually contains 50–70% methane and can be used directly in combined heat and power (CHP) units or upgraded to biomethane for injection into the natural gas grid or as vehicle fuel. Conversely, a digestate, the residue from the process, can be used as a soil amendment after stabilisation and pathogen reduction (see Figure 3). However, quality control is important to avoid contamination from heavy metals, plastics or glass fragments (Kabeyi and Olanrewaju, 2022a).

An important development in the recovery of energy from anaerobic digestion is the anaerobic membrane bioreactor (AnMBR), which combines the traditional AD process with membrane filtration to improve treatment performance and biogas yield. AnMBRs retain biomass and slow-growing methanogens in the reactor (independent of hydraulic retention time) allowing higher organic loading rates and a high quality, low solids effluent. Musa *et al.* (2018) reviewed the performance of AnMBR systems and reported organic loading rates of up to 4.85 kg COD/m3.day with chemical oxygen demand (COD) removal efficiencies of 95%, reaching as high as 99% during stable operation, along with biogas yields of approximately 150 L per kg of COD removed, of which about 73% was methane. These results show that AnMBR configurations could significantly enhance the pollutant removal and energy recovery performance of anaerobic digestion compared to conventional digesters, while membrane fouling, caused by suspended solids, fats, oils and greases and extracellular polymeric substances, is still the main operational issue that restricts wider commercial deployment (Musa, *et al.* 2018).

AD also boasts a number of environmental benefits. It reduces the amount of organic waste to landfills, reduces greenhouse gas emissions by capturing the methane that would have escaped from uncontrolled decomposition and helps renewable energy generation (Kabeyi and Olanrewaju 2022b). It also recovers energy and nutrients from waste, thus complying with the circular economy principles. The most economically feasible option for AD plants is integration into complete waste management systems, which include source separation, composting, and recycling (Waqas *et al.* 2023). MSW AD is under pressure however. The challenges are high capital cost, requirement of effective pre-sorting for removal of contaminants, and risk of process instability due to substrate fluctuation or ammonia inhibition (Piadeh, *et al.* 2024). Moreover, the penetration of the digestate market is limited by quality certification and legislative limitations in different places. AD despite the disadvantages is attracting global attention as sustainable option for landfilling and incineration of organic waste management.

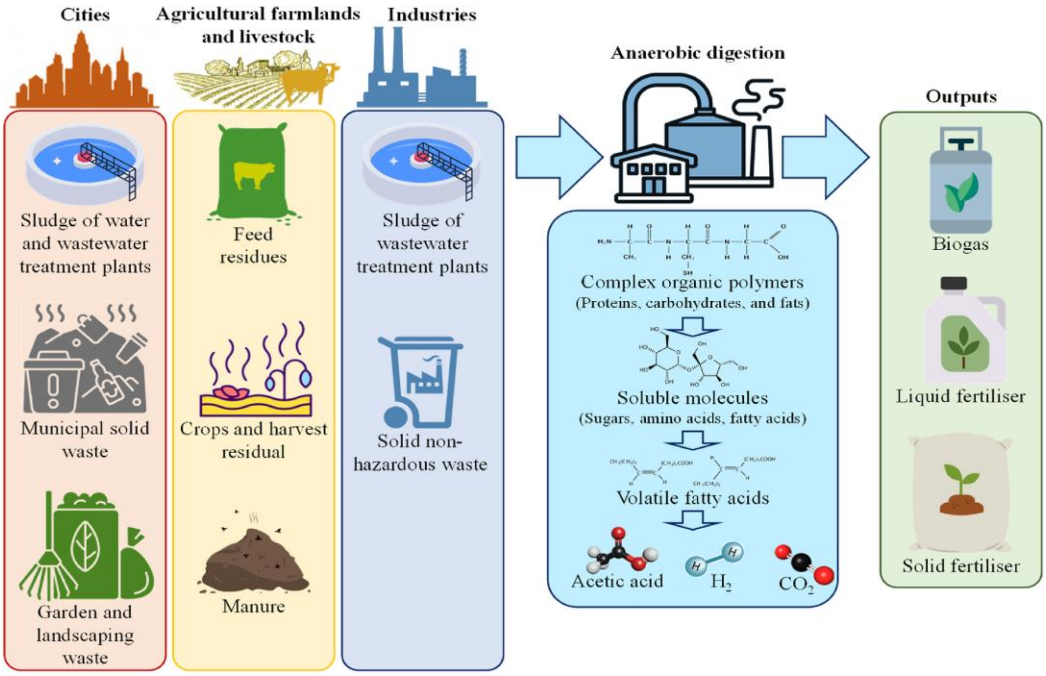

Figure 3: Schematic illustration of biorefinery inputs and outputs of AD processes (Piadeh, *et al.* 2024)

3.3 Landfill

When organic waste in a sanitary landfill decomposes under anaerobic conditions, a mixed gas commonly called landfill gas (LFG) is produced, consisting primarily of CH_4 (~40-60 %) and CO_2 (~30-50 %) along with moisture, trace nitrogen/oxygen, and non-methane organic compounds (Kumar, 2016). The idealized sequence of waste degradation process that occur in a landfill for a homogeneous volume of waste is shown in Figure 4. Initially, aerobic decomposition takes place until available oxygen is depleted, followed by acidogenic and acetogenic stages where organic acids and hydrogen are produced. In the methanogenic phase, methanogenic archaea convert intermediates such as acetate, hydrogen, and carbon dioxide into methane and carbon dioxide (Kumar, 2016).

The production of gas occurs a few months after the disposal of waste, attains a peak after a few years, and then gradually declines within a time frame of 15 to 25 years depending on factors like landfill conditions, management practices, and waste composition (Gavrila, *et al.* 2025). In any LFG-to-Energy system, a system of pipes and gas extraction wells is built in order to regulate the captured gas with minor negative pressure and avoid fugitive emissions as well as migration. The gas collected is channeled to a centralized processing facility where the gas is treated to get rid of moisture, particles, and pollutants like siloxanes and hydrogen sulphide (EPA, 2025). Following purification, the gas can be employed in various ways: it can be burned in microturbines, gas turbines, or internal combustion engines and produce electricity, or it can be applied in boilers for direct thermal applications, or it can be transformed into renewable natural gas which can be injected through pipelines or used as fuel for vehicles.

Using LFG for energy production has plenty of environmental and economic advantages. Methane is a significant greenhouse gas with global warming potential nearly 28 times higher than carbon dioxide's over a 100-year period. Thus, capturing methane and using its energy potential is able to really reduce greenhouse gases emissions as well as creating a renewable energy source. Moreover, LFG projects are capable of earning income from selling electricity, issuing carbon credits, and obtaining incentives for obtaining renewable energy, ensuring that they remain economically feasible.

Also, the technology enables integrated waste management systems, where energy can be extracted from existing landfills with minimal land usage (Shoqeir and Mansour, 2025).

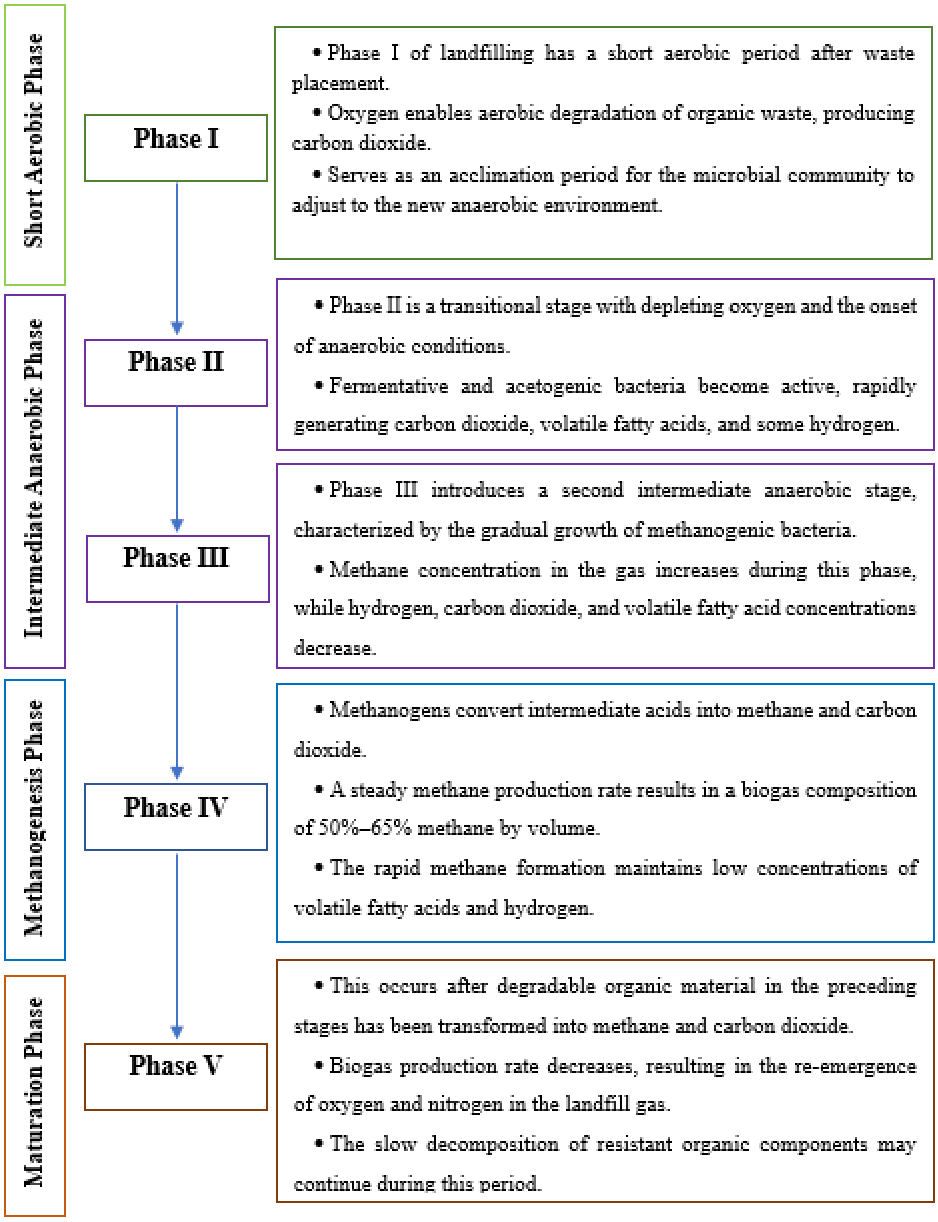

Figure 4: Waste degradation sequence in landfill (Amulah, 2024)

The system has some limitations but converting LFG into energy benefits the environment and economy. First, the calorific value of raw gas is much lower than conventional natural gas, which makes it difficult to use LFG for direct combustion. Moreover, the amount of gas produced is variable and depends on the waste's age, composition, moisture, and the landfill's design, which makes it difficult to predict the energy yield in the long run (Kerboua *et al.* 2025). Further, installation and maintenance of gas collection systems are capital-intensive, and efficiency depends on proper spacing of wells, cover integrity, and vacuum control. Also, in order to convert LFG into pipeline-grade biomethane, advanced purification systems should be used to eliminate impurities and moisture, which is cost-prohibitive (EPA, 2023). It is important to point out that landfill operation and the practice of anaerobic digestion do not mean that the two processes cannot be combined; instead, they can become complimentary steps of a complex waste conversion system. In the case of landfilling, its main function is waste disposal and containment because landfills only accept residual waste that is not diverted from the original source and produces landfill gas after some time. On the other hand, anaerobic digestion is designed to improve waste treatment processes because it allows creating perfect temperature, pH, and retention conditions for the same biological process that takes place in a landfill but occurs naturally and passively, to speed up degradation and receive biogas more efficiently. The connection between the discussed processes is landfill leachate, which is the waste product obtained as the result of landfill decomposition. This waste product can be processed in anaerobic digesters and co-digested with other organic materials, which will allow to produce more energy and ease leachate treatment problems at the site. The authors reviewed the integration opportunities presented by the combination of anaerobic digestion and leachate treatment and discovered that COD removal rates reached 78% and biogas methane content was 70%-75%, thus confirming the feasibility of this approach.

3.4 Gasification

Gasification is a thermochemical WtE process which converts carbonaceous materials in MSW into a combustible gas mixture called syngas, mainly consisting of CO, H2, CH4 and minor amounts of CO2. Gasification is conducted in a sub-stoichiometric oxygen environment (partial oxidation) at a temperature of 700 °C to 1,200 °C (Wang, *et al.* 2023) unlike incineration which is complete combustion with excess oxygen. Figure 5 is a simplified schematic of the gasification process.

In this process the solid waste is first dried and then pyrolysed to release volatile compounds after moisture removal. Partial oxidation-reduction reactions of the residual char and volatiles occur in the presence of a controlled amount of oxidant such as air, oxygen or steam (Zaccariello and Montagnaro, 2023). The main reactions are:

• Oxidation reactions, which supply heat to drive the process and

• Reduction reactions, which convert carbonaceous materials to syngas.

The syngas produced can be cleaned and used directly for electricity generation by internal combustion engines or gas turbines or further processed to liquid fuels and chemicals by catalytic synthesis. The volume of the solid residue called slag or char is greatly reduced and at times the residue may be used in construction materials if the environmental safety standards are met.

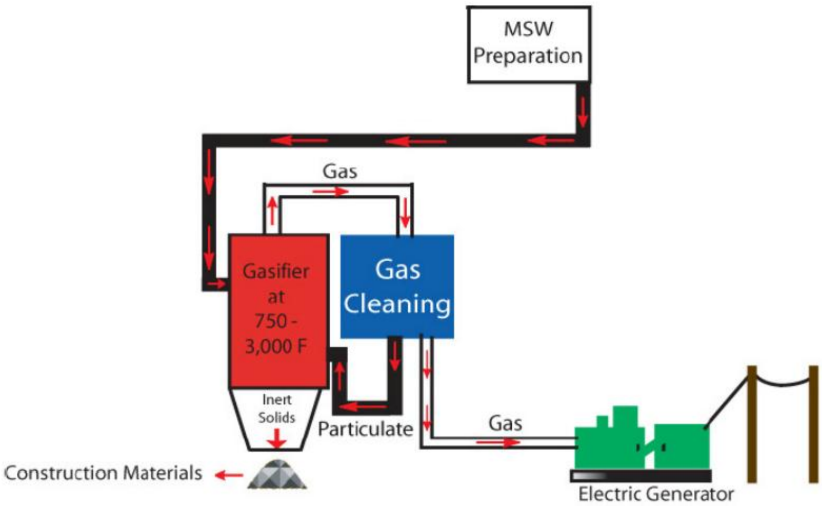

Figure 5: Overview of gasification process

Gasification has several advantages over conventional incineration. It runs under low oxygen conditions which reduces the pollution emitted and the amount of nitrogen oxides (NOx) and dioxins produced (Santana, *et al.* 2025). The possibility to utilize syngas in different ways increases energy efficiency of the process making gasification a more adaptable means of energy recovery. Additionally, gasification has the capacity to process a number of types of waste such as plastics, paper and biomass with minimal preparation.

Nevertheless, gasification of the unauthorized solid waste is a complicated technical and expensive process. Achieving a stable temperature and maintaining control over the reactions in the process is tricky due to various types of waste that are involved in the process representing a mixture that influences the uniformity and quality of syngas production. A vital problem is the production of tar, since hydrocarbons present in the syngas have to be properly removed from the gas, otherwise, there would be a problem with the system working well (Zaccariello and Montagnaro, 2023). The gas cleaning process also has to comply with strict standards, as well as a demand for syngas output. Nonetheless, gasification is considered to be a stepping stone solution for solid waste management in terms of a middle position between incineration and state-of-the-art technology for solid waste treatment (Ungureanu, *et al.* 2025).

3.5 Plasma Gasification

Plasma gasification is an advanced WtE technology based on advanced thermochemistry that uses plasma torches, devices that reach extremely high temperatures (often over ~3,000 °C), to convert MSW into syngas and a vitrified, inert slag. It is an evolution of the traditional gasification that uses plasma arcs to achieve higher energy density and more complete waste destruction (Sanlisoy and Carpinlioglu, 2017).

During plasma gasification, waste is fed into a reactor chamber where it is exposed to a plasma torch which ionises the gas (typically air, oxygen or steam) to produce a plasma plume. The high temperature causes the decomposition of the organic fractions of the waste in basic molecules such as CO and H2, while the inorganic fractions melt and upon cooling solidify in a glass-like slag (Mazzoni, *et al.* 2017). Generally, two main zones are involved in the process: (1) pyrolysis–gasification zone (organic decomposition into syngas); and (2) melting zone (conversion of inorganic components into inert slag). The syngas generated by plasma gasification is often of higher energy content and lower contaminants than that generated by conventional gasification, making it suitable for power generation, H2 production, or synthesis of fuels and chemicals after proper cleaning. The vitrified slag is largely non-leachable and can be reused as construction aggregate or disposed of with negligible environmental risk (Ramos and Rouboa, 2022).

Plasma gasification provides a lot of environmental benefits: near-total destruction of hazardous organic compounds (and hence low dioxin/furans levels), very high waste volume reduction (up to ~95%) and the encapsulation of heavy metals in the vitrified slag, which decreases leachate risk. The flexibility to treat different waste streams increases its applicability in integrated waste management schemes (Ramos and Rouboa, 2022). But the plasma gasification is still economically and technically challenged with high capital and operational costs due to high energy consumption of plasma torches, expensive refractory and maintenance costs and requirement of sophisticated syngas cleaning system. Pilot plants have been successful but commercial implementation is still limited (Ramos and Rouboa, 2022; Xiao, *et al.* 2020).

4. Comparative Analysis of the WtE Technologies

As earlier stated, the choice of technology depends on several factors including waste composition, energy recovery efficiency, environmental regulations, and socio-economic conditions. Table 1 presents a summary of different WtE technologies and the types of waste they are capable of handling.

Table 1: WtE technologies and the type of waste they can handle (Soltanian, *et al.* 2022)

	Organic waste	Paper and cardboard	Wood waste	Glass/ metals	plastics	Textiles	Rubber/ leather
Recycling	✗	✓	✗	✓	✓	✓	✓
Land-filling	✓	✓	✓	✓	✓	✓	✓
Anerobic digestion	✓	✓	✓	✗	✗	✗	✗
Compositing	✓	✓	✓	✗	✗	✓	✗
Thermo-mechanical	✓	✓	✓	✗	✗	✓	✓
Incineration	✓	✓	✓	✓	✓	✓	✓
Pyrolysis	✓	✓	✓	✗	✗	✓	✓
Gasification	✓	✓	✓	✗	✗	✓	✓
Plasma gasification	✓	✓	✓	✓	✓	✓	✓

4.1 Technical Parameters

The technical performance of WtE technologies is determined by their energy conversion efficiency, feedstock flexibility, processing capacity and operating conditions (Beyene, *et al.* 2018). These parameters determine the suitability of a technology for a given waste type, and the ability of the technology to reliably produce energy. Technologies such as incineration and gasification are characterised by a higher throughput and thermal efficiency, but they require significant process control. Anaerobic digestion operates under milder conditions and is best suited for organic waste (Obileke, *et al.* 2023; Inayat, *et al.* 2025). Table 2 shows the main technical characteristics of the major WtE technologies.

4.2 Environmental Parameters

The environmental performance is an important consideration in the selection of WtE technologies due to its direct impacts on air quality, greenhouse gases emissions and residue management (Dong *et al.* 2019). The level of such emissions as NOX, SOX and dioxins depends on the type of process and pollution control systems used. Likewise, water use, ash production, and greenhouse gas reduction potential vary by technology. Table 3 summarizes the environmental characteristics of the major WtE technologies.

Table 2: Technical parameters of various WtE technologies

Technology	Efficiency (%)	Feedstock Flexibility	Throughput Capacity	Operating Temperature	Operating Pressure
Incineration	20–30 (electrical); 80–90 (combined heat and power)	High – handles mixed MSW with minimal pre-treatment	50–3,000 tonnes/day	850–1,100 °C	Atmospheric to slight positive pressure
Gasification	30–40 (electrical); 60–80 (syngas energy)	Medium–High – requires some sorting, moisture content <30%	10–500 tonnes/day	700–1,500 °C	1–70 bar depending on gasifier type
Pyrolysis	25–35 (bio-oil/char); 50–70 (combined products)	Medium – requires dry feedstock (<15% moisture), pre-sorted material	5–200 tonnes/day	400–800 °C	Atmospheric to slight vacuum
Anaerobic Digestion	35–40 (biogas to electricity); 55–65 (CHP systems)	Low–Medium – organic fraction only, solids content <40%	5–100 tonnes/day	35–55 °C (mesophilic); 55–70 °C (thermophilic)	Atmospheric to 0.1 bar
Plasma Gasification	25–35 (electrical); 65–75 (syngas energy)	Very High – handles hazardous waste and all waste types	50–1,000 tonnes/day	3,000–10,000 °C in plasma zone	Atmospheric to 5 bar

Table 3: Comparison of WtE technologies based on environmental factors

Technology	Air Emissions (NO_X, SO_X, Dioxins)	Water Usage and Wastewater Generation	Ash and Residue Management	Greenhouse Gas Emissions
Incineration	Moderate–high; controlled with modern flue gas systems	High (flue gas scrubbing produces wastewater)	Large quantities of bottom and fly ash (hazardous)	Moderate; depends on fossil content of waste
Gasification	Low–moderate; cleaner than incineration with syngas cleanup	Moderate (gas cleaning and cooling)	Low volume of inert slag/ash	Lower than incineration if syngas efficiently used
Pyrolysis	Low–moderate; VOCs and tars possible if not managed	Moderate (cooling and condensation processes)	Char and tar residues may require treatment	Low to moderate; potential carbon sequestration with biochar
Anaerobic Digestion	Very low; minimal NO_X, SO_X, or dioxins	Moderate (digestate dewatering and treatment)	Digestate usable as fertilizer or soil amendment	Very low; methane recovery offsets fossil fuels
Plasma Gasification	Very low; high destruction efficiency of pollutants	Low–moderate (gas scrubbing)	Vitrified inert slag, minimal residue	Low; effective carbon utilization when syngas used

4.3 Economic Parameters

The reason why WtE systems are economically effective depends on investment in fixed assets, operation and maintenance (O and M) costs, levelized cost of energy (LCOE), and sources of profit earned (Hadidi and Omar, 2017). Incineration and gasification need high amounts of fixed assets and O and M costs, but they still may generate profits in the form of revenue from electricity and disposal fees. Anaerobic digestion does not need such investments and, moreover, produces income from biogas and fertilizer (Marefat *et al.* 2025; Tahiru *et al.* 2024). Table 4 provides a comparative overview of the economic parameters for key WtE technologies.

4.4 Social Parameters

Important for the implementation of WtE projects are the social factors, such as public acceptance, health and safety, job creation and local economic benefits. However, incineration is generally opposed by the public because of the environmental dangers involved (Huang, *et al.* 2015). However, the environmental and agricultural benefits of anaerobic digestion are widely established (Huang, 2024). Gasification and plasma gasification require trained personnel but can stimulate local employment and technology transfer (Kaushal, *et al.* 2024). Table 5 presents the social performance comparison among the main WtE technologies.

Table 4: An overview of the economic parameters for key WtE technologies

Technology	Capital Cost	Operating and Maintenance Cost	Levelized Cost of Energy (LCOE)	Revenue Streams
Incineration	High	High (flue gas cleaning, ash disposal)	Moderate	Electricity, heat, gate fees, metal recovery
Gasification	High	High (gas clean-up and tar removal)	Moderate	Syngas, electricity, heat, fuels, gate fees
Pyrolysis	Moderate–high	Moderate (tar/catalyst handling)	Moderate–high	Bio-oil, char, syngas, gate fees
Anaerobic Digestion	Low–moderate	Moderate (biogas and digestate management)	Low–moderate	Biogas, fertilizer, heat, gate fees
Plasma Gasification	Very high	High (power use, torch maintenance)	High	Syngas, slag by-products, high gate fees for hazardous waste

Table 5: Social parameters of WtE technologies

Technology	Public Acceptance	Health and Safety	Job Creation	Local Economic Benefits
Incineration	Often low due to emission concerns	Strict monitoring and control required	Moderate–high for large facilities	Contributes to energy and waste management infrastructure
Gasification	Moderate–good if emissions well controlled	Syngas handling risks require trained staff	High for skilled operators and maintenance	Supports industrial symbiosis and fuel production
Pyrolysis	Mixed; dependent on transparency and emission control	High-temperature and tar handling risks	Moderate	Provides local value chains (biochar, bio-oil markets)
Anaerobic Digestion	High; considered environmentally friendly	Low risks; controlled biogas handling	High (collection, operation, and agriculture sectors)	Strengthens circular economy and rural development
Plasma Gasification	Mixed; positive for hazardous waste treatment	High-temperature and electrical hazards	High for technical roles	Attracts specialized industries and high-value processing

4.5 Other Parameters

Besides technical, environmental and economic constraints, other elements such as scalability , technology maturity and operational flexibility play an important role in the assessment of long term feasibility . Incineration and anaerobic digestion are mature technologies and common, whereas gasification, pyrolysis and plasma gasification are more flexible but less mature for large scale MSW applications (Inayat, *et al.* 2025). These additional comparative metrics for the main WtE technologies are provided in Table 6.

Table 6: Scalability, maturity and flexibility of WtE technologies

Technology	Scalability	Technology Maturity	Flexibility
Incineration	High – suitable for city-scale systems	Very mature – widely commercialized	Moderate – limited to mixed MSW
Gasification	High – industrial and modular options	Mature for biomass, emerging for MSW	High – adaptable to multiple feedstocks and outputs
Pyrolysis	Moderate – suited for small to medium plants	Semi-commercial – advancing for plastics/biomass	Moderate – depends on feedstock pre-treatment
Anaerobic Digestion	High – scalable modular units	Very mature – proven for organic waste	Limited – requires biodegradable feedstocks
Plasma Gasification	Moderate – industrial-scale units costly	Emerging – few large commercial plants	Very high – handles all waste types and hazardous waste

Among the various WtE technologies examined so far, the plasma gasification technology is well-known to be the most efficient and environmentally safe technology. This is a high temperature technology (> 3,000 °C) capable of converting wastes to syngas and inert vitrified slag without producing toxic emissions. The technology has good feedstock flexibility, low GHG emissions, and good energy recovery performance compared to traditional technologies such as incineration and pyrolysis. Although initial capital and operational costs are still high, obtaining near-zero waste and producing clean energy makes this technology a feasible long-term solution in the field of waste management, especially in urbanised areas. The advantages of plasma gasification are confirmed by exergy analysis performed by recent studies. This methodology helps to assess thermodynamic efficiency and sustainability of energy conversion systems. Amulah (2024) conducted exergy analysis in order to compare the major WtE technologies and showed that plasma gasification technology has the highest overall exergy efficiency and the lowest exergy destruction. The study proves that plasma gasification technology has good performance in relation to energy recovery while incineration remains the most developed and widely used technology. The full comparative analysis is represented by the parameters shown in Figure 6 in Amulah (2024).

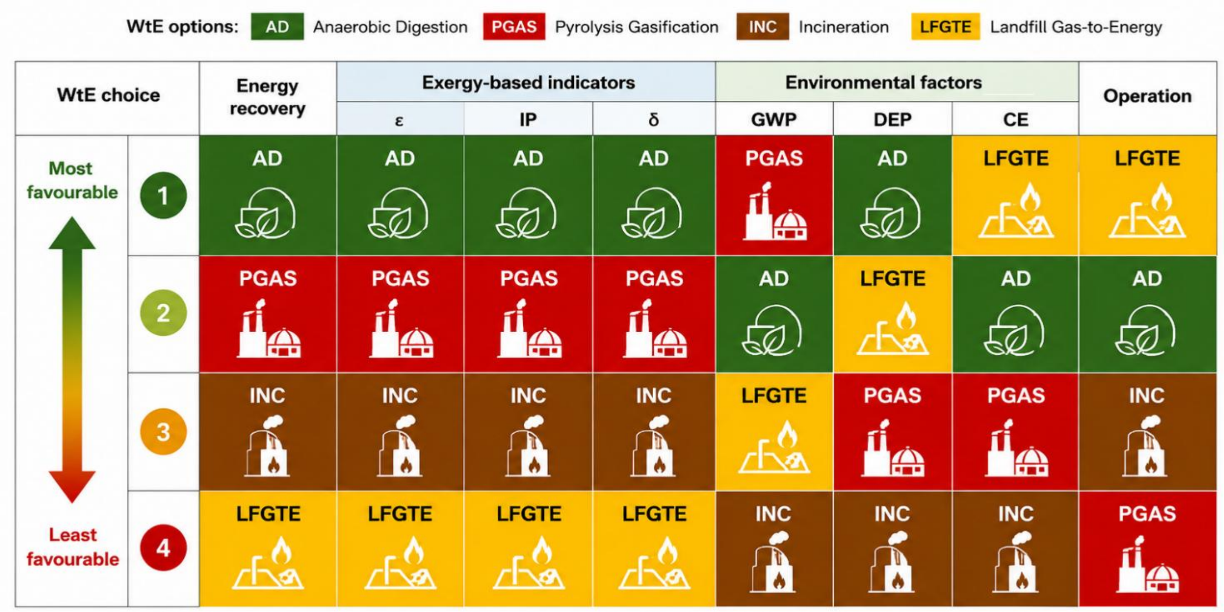

Figure 6: Choice of WtE technologies based on some weighted parameters

5. Conclusion

This study provides a review on five major waste-to-energy technologies (incineration, anaerobic digestion, landfill gas-to-energy, gasification, and plasma gasification) based on technical, environmental, economic, and social perspectives. There is a clear hierarchy in terms of energy conversion efficiency: anaerobic digestion coupled with combined heat and power (CHP) offers the highest overall efficiency (55–65%), followed closely by incineration under CHP (80–90% total for heat and power but 20–30% for electricity only), while plasma gasification provides the best syngas-based energy recovery (65–75%) of the thermochemical methods, ahead of conventional gasification (60–80% as syngas energy) and pyrolysis (50–70% for combined products). Landfill gas-to-energy is the least efficient option in terms of energy density and long-term predictability but is still the lowest cost option to recover energy from waste already destined for disposal. However, there is no one technology that is best across all criteria when efficiency is considered. Incineration and anaerobic digestion are the most mature and widespread technologies due to their proven reliability, however, incineration has a higher environmental burden from air emissions and ash residues while anaerobic digestion has the best environmental profile and social acceptance but is limited to biodegradable feedstocks. Gasification and plasma gasification offer increased feedstock flexibility to plastics, hazardous waste and mixed residues. Plasma gasification reports the highest waste volume reduction (up to 95%) and exergy efficiency (up to 42%) in comparative exergy assessments (Amulah, 2024) but still suffers from high capital costs and limited commercial-scale deployment. The most readily available in economic terms is landfill gas-to-energy, but technically it is the least efficient and the most dependent on waste composition and site-specific conditions.

The following technological directions are suggested for future studies: (i) techno-economic and life-cycle assessments directly comparing hybrid WtE configurations (e.g. AD–landfill leachate co-treatment or AD–gasification integration) with single-technology systems on the basis of region-specific waste compositions; (ii) pilot- and full-scale trials of anaerobic membrane bioreactor (AnMBR) configurations for organic waste and leachate streams, to validate the higher COD removal and biogas yields reported at laboratory scale under real operating conditions; (iii) research into cost-reduction strategies for plasma gasification, particularly around torch energy consumption and refractory material durability, to improve its economic competitiveness relative to conventional gasification; and (iv) standardised exergy- and efficiency-reporting frameworks across

WtE studies, to enable more consistent cross-technology comparison than currently possible from the literature.

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