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Thermal Plasma Gasification of Municipal Solid Waste: Principles, Technological Advances, Challenges, and Future Prospects

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Abstract
The rapid increase in municipal solid waste (MSW) generation, driven by population growth, urbanisation, industrialisation, and changing consumption patterns, has intensified the demand for sustainable waste management technologies capable of reducing environmental impacts while recovering valuable resources. Among the available treatment methods, thermochemical conversion technologies have attracted considerable attention because of their ability to simultaneously reduce waste volume and generate useful energy products. This review provides a comprehensive evaluation of the major thermochemical treatment technologies for MSW, including incineration, pyrolysis, gasification, plasma gasification (PG), and hydrothermal carbonisation (HTC), with particular emphasis on TP gasification as an advanced waste-to-energy technology. The review discusses the fundamental characteristics of thermal plasma, plasma generation techniques, plasma torch configurations, and the reaction mechanisms governing PG. It further examines the influence of operating parameters, including plasma temperature, gasifying agent, equivalence ratio, steam-to-feedstock ratio, and feedstock composition, on syngas quality, energy recovery, and process efficiency. Recent advances in experimental investigations, thermodynamic modelling, process simulation, and techno-economic assessments are critically analysed to evaluate the current state of PG technology. The findings indicate that PG offers several advantages over conventional thermochemical processes, including exceptionally high waste destruction efficiency, near-complete elimination of tar, reduced formation of dioxins and furans, production of hydrogen- and carbon monoxide-rich synthesis gas, and generation of environmentally stable vitrified slag suitable for beneficial reuse. Despite these advantages, high capital investment, significant electrical energy demand, and limited commercial-scale deployment remain the principal barriers to widespread implementation. The review also identifies important research gaps, particularly the limited application of PG to petroleum-derived hazardous wastes and the need for integrated studies combining waste characterisation, process optimisation, product evaluation, environmental assessment, and techno-economic analysis. Future research should focus on developing energy-efficient plasma systems, advanced reactor designs, renewable energy integration, artificial intelligence-assisted process optimisation, and comprehensive life-cycle assessment to improve the commercial viability and environmental sustainability of PG. Overall, thermal plasma gasification is identified as one of the most promising technologies for sustainable MSW management and resource recovery, with significant potential to support the transition towards a circular economy and low-carbon energy systems.

Keywords: *Municipal solid waste, Thermal plasma, Plasma gasification, Waste-to-energy, Thermochemical conversion, Vitrified slag, Resource recovery.*

1.0 Introduction

Rapid population growth, industrialisation, urbanisation, and changing consumption patterns have led to a substantial increase in the generation and accumulation of municipal and industrial solid waste worldwide. Globally, approximately 2.56 billion metric tonnes of municipal solid waste (MSW) are generated annually, and this figure is projected to rise to about 3.86 billion metric tonnes by 2050 [1]. The continuous increase in waste generation poses serious environmental, economic, and public health challenges, particularly in developing countries where waste management infrastructure remains inadequate. Consequently, the development of efficient and sustainable waste management strategies has become a global priority. Among the available waste management options, thermochemical conversion technologies have gained considerable attention because of their ability to reduce waste volume while simultaneously recovering energy and valuable products. Unlike conventional disposal methods such as landfilling, thermochemical processes convert waste into useful forms of energy, fuels, and chemical feedstocks through the application of heat, either in the presence or absence of oxygen [2]. In addition to significantly reducing the mass and volume of waste requiring final disposal, these technologies contribute to resource recovery, reduce dependence on fossil fuels, and support the transition towards a circular economy. The principal thermochemical treatment technologies include incineration, pyrolysis, gasification, plasma gasification (PG), and hydrothermal carbonisation (HTC), each operating under different reaction conditions and producing distinct products.

1.1 Literature Search and Selection Methodology

In this review a structured literature-search approach was adopted in order to identify relevant publications on thermal plasma gasification of municipal solid waste (MSW), hazardous waste, plastic waste, and petroleum oily sludge. The literature search focused primarily on peer-reviewed journal articles, conference and seminar

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papers, reviewed articles and relevant academic theses addressing thermal plasma technology, plasma pyrolysis of waste, plasma gasification of waste, and plasma vitrification processes. Searches were conducted using combinations of major keywords and Boolean operators, including thermal plasma, plasma gasification, and plasma gasification of municipal solid waste, plasma pyrolysis, MSW gasification, and plasma treatment of hazardous waste. Additional search were performed using combinations of these terms with specific feedstock such as plastics waste, biomedical waste, petroleum oily sludge, and refinery waste. Studies were selected based on their relevance to the objective and scope of the study. Priority was given to article publications that provided experimental results, validated modelling, or simulation results, thermodynamic analysis, process design and optimisation data, or techno-economic data directly relevant to plasma conversion of waste. Studies were also considered where they provided established theoretical background necessary for explain thermal plasma gasification of waste, plasma torch operation, and plasma gasification mechanisms. Publications that were unrelated to thermal plasma conversion of waste, lack sufficient technical information or focused exclusively on applications outside the scope of waste treatment and resource recovery were excluded.

The relevant of each selected publication was assessed according to the extent to which it contributed evidence to one or more of the principal themes of the review: (i) characteristics and composition of MSW; (ii) thermal plasma generation and plasma torch technology; (iii) plasma gasification mechanisms; (iv) effect of operating parameters on syngas composition and energy performance; (v) treatment of MSW and hazardous waste; (vi) modelling, simulation and optimisation; (vii) environmental performance and residue vitrification; and (viii) economic and commercialisation considerations. Particular consideration was given to documented studies reporting measurable performance indicators such as syngas composition, yields of hydrogen and carbon monoxide, carbon conversion efficiency, energy efficiency, tar reduction efficiency, volume and mass reduction of waste, and economic indicators. The quality of the selected literature material was assessed by considering the credibility of the publication source, clarity of the research methodology, adequacy of experimental or modelling procedures, transparency of reported operating conditions, reliability and completeness of the reported results, and, where applicable, validation of simulation or thermodynamic models against experimental data. Greater evidence weight was assigned to peer-reviewed studies with clearly described methodologies, reproducible operating conditions, quantitative results, and experimental validation. Review articles and books were primarily used to established theoretical foundations and provide broader technological context, whereas experimental and validated modelling studies were used to support specific performance claims. Where studies reported limitations, uncertainties, high energy consumptions, scale-up constraints, or contradictory findings, these were retained in the synthesis rather than excluded solely because they did not support the advantages of plasma gasification.

The literature was subsequently organised thematically according to experimental investigations, modelling and simulation, thermodynamic and exergy analysis, process optimisation, environmental performance, and techno-economic assessment. This approach enabled comparison of findings across different feedstocks and operating conditions and provided a basis for identifying areas where evidence remains limited. In particular, the review identified a comparatively small body of research addressing plasma gasification of petroleum oily sludge and related refinery waste, despite the broader literature on MSW, plastic waste, biomedical waste, and other hazardous waste. The evidence gap provides an important basis for recommending further research on integrated feedstock characterisation, plasma treatment, product assessment, environmental performance, process optimisation and techno-economic evaluation.

2.0 Thermochemical Waste Conversion Technologies: Principles, Products, Advantages, and Limitations

The principal thermochemical treatment technologies include incineration, pyrolysis, conventional gasification, plasma gasification (PG), and hydrothermal carbonisation (HTC), each characterisaed by distinct reaction conditions, conversion mechanisms, and product stream. Incineration is the most mature and widely implemented thermochemical waste treatment technology. It involves the complete combustion of solid waste in the presence of excess oxygen at temperatures typically ranging from 850 to 1,100 ^{o}C. During the process, combustible materials are oxidised to produce carbon dioxide (CO_2), water-vapour, flue gases, ash, and substantial quantities of heat [3]. This thermal energy can be recovered to generate electricity and district heating, making incineration an established waste-to-energy technology. Furthermore, incineration achieves a substantial reduction in waste volume and mass, typically between 80 and 90%, while effectively destroying pathogens and hazardous organic compounds. Despite these advantages, the process presents several environmental challenges. The formation of pollutants such as nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter, dioxins, furans, and heavy metals necessitates the installation of sophisticated air pollution control systems [4]. In addition, fly ash and bottom ash generated during combustion require careful treatment and disposal because of their potentially hazardous nature. Consequently, although incineration remains an effective waste treatment option, its high capital and operating costs, together with stringent environmental regulations, have encouraged the development of alternative thermochemical technologies.

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Pyrolysis has emerged as an attractive alternative because it thermally decomposes waste in an oxygen-deficient environment rather than combusting it. Typically conducted at temperatures between 300 and 800 °C, pyrolysis converts MSW into three principal products: bio-oil, syngas, and char [5]. The bio-oil is obtained by condensing volatile compounds released during thermal decomposition, while the non-condensable gases constitute the combustible syngas after appropriate cleaning. The remaining solid residue is a carbon-rich char that may be utilised as a fuel, adsorbent, or soil amendment following suitable treatment. The distribution of these products depends largely on operating conditions such as temperature, heating rate, and residence time. Compared with incineration, pyrolysis generally produces lower atmospheric emissions and offers greater opportunities for recovering valuable fuels and chemicals from mixed plastic and biomass wastes [6]. However, product quality is highly dependent on feedstock composition, and the process often requires extensive feedstock preparation and sophisticated process control, thereby increasing operational complexity.

Gasification represents another important thermochemical conversion route in which waste undergoes partial oxidation at temperatures typically between 700 and 1,500 °C using a controlled supply of oxygen, air, steam, or a combination of these gasifying agents [7]. Unlike incineration, gasification converts the combustible fraction of the waste primarily into synthesis gas (syngas), comprising carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and smaller quantities of carbon dioxide (CO_2). Following appropriate cleaning, syngas can be used for electricity generation, industrial heating, hydrogen production, and the synthesis of chemicals and liquid fuels. Gasification generally exhibits higher energy efficiency than conventional incineration while producing lower emissions and smaller quantities of residual ash. Nevertheless, the technology requires relatively homogeneous feedstocks, efficient gas-cleaning systems, and considerable capital investment, all of which remain significant barriers to its widespread adoption [8].

Among the emerging thermochemical technologies, Plasma gasification (PG) has attracted increasing research interest because of its exceptional waste destruction capability and superior environmental performance. PG employs a plasma torch to generate extremely high temperatures, typically between 2,000 and 10,000 °C, enabling the almost complete decomposition of organic materials into hydrogen- and carbon monoxide-rich syngas [9]. Simultaneously, inorganic constituents are melted and vitrified into an inert glass-like slag that can potentially be utilised in road construction and other civil engineering applications. The exceptionally high reaction temperatures suppress the formation of hazardous organic pollutants such as dioxins and furans while ensuring high destruction efficiencies for hazardous and difficult-to-treat wastes [10]. Furthermore, the process offers considerable potential for energy recovery and resource utilisation. Despite these advantages, PG constrained by its high electrical energy demand, substantial capital costs, complex operational requirements, and relatively limited commercial deployment compared with conventional incineration and gasification technologies.

Hydrothermal carbonisation (HTC) provides a fundamentally different approach to thermochemical waste conversion. Unlike the high-temperature processes discussed above, HTC treats wet organic waste in hot compressed water at temperatures of approximately 180-250 °C under elevated pressure [11]. An important advantage of HTC is that it does not require prior drying of the feedstock, making it particularly suitable for high-moisture wastes such as food waste, sewage sludge, and other biodegradable materials. The principal product is hydrochar, an energy-dense carbonaceous material that may be utilised as a solid fuel or soil amendment following appropriate characterisation and environmental assessment. Additional benefits include improved fuel properties, reduced moisture content, and enhanced handling characteristics of the treated material. However, the process is generally limited to biodegradable feedstocks, requires pressure-resistant reactors, and produces a liquid by-product that often requires further treatment before disposal or reuse [12]. Each of these thermochemical technologies possesses distinct advantages and limitations, making their suitability dependent on the characteristics of the waste, the desired products, the environmental considerations, and the economic feasibility. Consequently, selecting an appropriate treatment technology requires careful evaluation of its technical performance, environmental impacts, energy recovery potential, and commercial viability. A comparative summary of the major thermochemical treatment technologies is presented in Table 1.

In summary, thermochemical treatment technologies provide sustainable alternatives to landfilling by converting MSW into useful energy and valuable products. Incineration is the most mature and widely implemented technique for large-scale waste reduction and energy recovery. Pyrolysis and gasification are increasingly attractive because they recover fuels and chemicals with potentially lower emissions. PG offers superior waste destruction but remains expensive, while HTC is particularly suitable for wet organic waste streams due to its ability to process high-moisture feedstock without prior drying. The selection of a suitable thermochemical process depends on waste composition, moisture content, desire products, economic feasibility, and environmental considerations. This paper focuses on the application of PG for the treatment of domestic and hazardous waste. The paper is organized into three main sections: an overview of the general characteristics of MSW, background information on plasma treatment technology, including its classification, characteristics, and generation, and the application of PG to MSW treatment.

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Table 1: Comparative characteristics, products advantages and limitations of major thermochemical waste treatment technologies

Technology	Reaction environment	Operating temp. (^{o}C)	Conversion mechanism	Main products	Major advantages	Key limitations	Typical application
Incineration /combustion	Excess oxygen	850-1,100	Complete combustion/oxidation	Heat, electricity, flue gas, bottom and fly ash	Mature and commercially established, substantial mass and volume reduction, effective destruction of pathogens and organic contaminants	Formation of NO_X, SO_X, particulate, dioxins and furans, ash management, relatively high environmental control requirement	Large scale waste treatment and energy recovery
Pyrolysis	Oxygen-free atmosphere	300-800	Thermal decomposition in the absence of oxygen	pyro oil, combustible gases/syngas and char	Produces fuels and chemicals feedstock, lower atmospheric emission, enable product recovery	Product distribution depend strongly on feedstock and operating conditions, requires feedstock preparation and process control	Fuel, chemical and material recovery
Conventional gasification	Limited oxygen, air or steam	700-1,500	Partial oxidation and gas-solid/ gas phase reactions	Syngas, char and slag/ash	Produces energy-rich syngas for power, hydrogen synthetic fuels, generally lower emissions and residual ash than incineration	Sensitive to feedstock characteristics, tar formation and gas cleaning , relatively high capital cost	Electricity, hydrogen and synthetic fuels production
Plasma gasification (PG)	Limited oxygen/air/steam with external plasma energy	2,000-10,000	Plasma-assisted pyrolysis, gasification, cracking and reforming	H_2/CO-rich syngas, vitrified slag and recoverable metals	Very high waste destruction efficiency, near complete tar destruction, reduced formation of dioxins/furans, vitrification of inorganic matter, high quality syngas and resource recovery	High electrical energy demand, high capital and operating cost, complex operation, limited commercial scale deployment	MSW, hazardous waste, biomedical waste and other difficult-to-treat waste, energy and resource recovery
Hydrothermal carbonisation (HTC)	Hot compressed water, no direct oxygen requirement	180-250	Hydrothermal conversion of wet organic matter	Hydrochar, process water and gases	Suitable for high-moisture feedstock, eliminates the need for prior drying, improves fuel and handling properties	Mainly applicable to biodegradable/wet organic waste, requires pressure-resistant reactors, process water may require treatment	Treatment and valorisation of food waste, sewage sludge, and other wet organic waste

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2.1 Municipal Solid Waste Composition and Characteristics

Municipal solid waste (MSW) is a heterogeneous mixture comprising a wide range of materials, including food waste, paper, plastics, wood, textiles, glass, metals, and other organic and inorganic constituents. It is generated primarily from households, markets, commercial establishments, institutions, and other urban activities. Owing to its diverse sources, the composition of MSW varies considerably across countries and regions and is influenced by several factors, including socioeconomic status, the level of urbanisation, industrial development, lifestyle, cultural practices, and consumption patterns [13]. These variations not only affect the quantity of waste generated but also determine the selection and efficiency of appropriate waste management and resource recovery technologies. In developed countries such as the United Kingdom and the United States, higher living standards and greater consumption of packaged goods result in MSW containing relatively large proportions of plastics, paper, metals, electronic waste, and other non-biodegradable materials [14]. Conversely, in developing countries, including Nigeria and India, MSW is dominated by biodegradable organic materials such as food waste, agricultural residues, leaves, and wood [15]. This difference largely reflects lower levels of industrialisation, greater dependence on fresh agricultural produce, and comparatively lower consumption of heavily packaged products.

Table 2 presents the typical composition of MSW in developing countries, illustrating both the heterogeneous nature of the waste stream and the predominance of biodegradable organic materials. The data indicate that organic waste, comprising food waste and green waste, constitutes the largest fraction of MSW, accounting for approximately 50-70% of the total waste generated [16]. This high organic content is a characteristic feature of many developing countries, particularly in Africa and parts of Asia, where fresh food consumption is high, the use of packaging materials is relatively limited, and a substantial proportion of the population depends on agricultural products for daily living. Although biodegradable waste remains the dominant component, the proportion of plastic waste has increased considerably in recent years, representing approximately 8-15% of the total MSW stream [17]. This trend reflects rapid urbanisation, population growth, changing consumer lifestyles, increased industrial activities, and the widespread use of single-use plastic packaging. In contrast, paper and cardboard typically account for only 5-12% of the waste stream, primarily because of lower consumption of packaged goods and the common practice of reusing paper products before their final disposal. These variations in waste composition have important implications for the selection, design, and optimisation of thermochemical waste treatment technologies, as feedstock characteristics strongly influence process efficiency, product distribution, energy recovery, and environmental performance.

Table 2: Typical Composition of MSW in the developing nations [17]

Waste Component	**Typical Composition (%)**
Organic (food and green waste)	50–70
Plastics	8–15
Paper and cardboard	5–12
Glass	2–6
Metals	2–5
Textiles	2–8
Wood	1–4
Rubber and leather	1–3
Other/Inert materials (soil, ash, stones, ceramics)	5–20

Glass and metals account for about 2-6% and 2-5%, respectively. In many developing countries, informal waste pickers recover a considerable proportion of these materials before final disposal, thereby reducing their abundance in municipal waste while providing economic opportunities for low-income communities [18]. Textiles contribute between 2-8%, reflecting increased consumption of clothing and household fabrics. Wood, accounting for 1-4%, originates primarily from furniture, construction activities, and yard waste, while rubber and leather, representing 1-3%, arise mainly from footwear, vehicle components, and household products. The proportion of other inert materials, including soil, ash, stones, ceramics, and construction debris, varies considerably from 5-20%. This wide variation is often associated with inadequate waste segregation at source, street sweeping practices, open dumping, and the disposal of construction and demolition wastes together with household refuse [19]. High inert content reduces the overall calorific value of MSW and adversely affects the efficiency of energy recovery technologies by increasing ash production and lowering the combustible fraction of the feedstock.

Summarily, the composition of the MSW in the developing nations is dominated by biodegradable organic matter with moderate quantities of combustible recycling materials such as plastics, paper, and textile. The predominance of organic waste provides considerable opportunities for resource recovery through composting, anaerobic digestion, and appropriately designed thermochemical processes.

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2.2 Thermal Plasma and Plasma Torch Technology

Plasma is commonly referred to as the fourth state of matter, following the solid, liquid, and gaseous states. It is estimated to constitute approximately 99% of the visible matter in the universe and consists of an electrically conductive gas containing chemically reactive species such as free electrons, ions, radicals, and neutral particles [20] [21]. The presence of these charged particles enables plasma to conduct both heat and electricity efficiently. Depending on the extent of ionisation, plasma may exist as either fully ionised or partially ionised matter. Fully ionised plasma is characterised by a degree of ionisation approaching unity, whereas partially ionised plasma exhibits ionisation levels between zero and unity [22]. Owing to its unique physicochemical properties, plasma has found extensive applications in materials processing, surface coating, thin-film deposition, cutting and welding operations, electronics manufacturing, biomedical engineering, and environmental remediation, particularly in waste treatment technologies.

Based on its thermodynamic characteristics, plasma is generally classified into high-temperature plasma and low-temperature plasma. High-temperature plasma, often referred to as fusion plasma, exists under extremely energetic conditions in which electrons, ions, and neutral particles are in thermodynamic equilibrium, typically at temperatures exceeding 50,000 K [23]. Such plasmas are primarily associated with nuclear fusion research and astrophysical phenomena and are not commonly employed for industrial waste treatment.

Low-temperature plasma is further categorised into thermal plasma (TP) and non-thermal plasma (NTP), depending on the thermal equilibrium among its constituent particles. In thermal plasma, electrons, ions, and neutral species are essentially in thermal equilibrium and possess nearly identical temperatures [24]. This equilibrium results in an exceptionally high heat flux and energy density, making TP highly suitable for high-temperature industrial applications. Artificial TP is commonly generated using plasma torches or microwave plasma systems, both of which produce temperatures sufficiently high to decompose virtually all organic materials. Consequently, TP has become one of the most promising technologies for waste treatment, where organic components are converted into hydrogen- and carbon monoxide-rich synthesis gas (syngas), while inorganic constituents are vitrified into a chemically stable glass-like slag suitable for potential reuse in construction applications [25]. In contrast, non-TP operates under non-equilibrium conditions in which electrons possess significantly higher temperatures than ions and neutral particles, which remain close to ambient temperature [26]. Under these conditions, the applied electrical energy is transferred predominantly to the electrons rather than to the bulk gas, producing highly energetic electrons without causing substantial heating of the surrounding medium. This characteristic makes non-TP particularly suitable for processing temperature-sensitive materials, including polymers, biomedical materials, electronic components, and biological tissues, where excessive heating would be detrimental.

Among the various plasma technologies, TP generated by electric arc discharge has become the most widely utilised for waste treatment because of its exceptionally high energy density and destruction efficiency. TP may be generated using either electrical energy, through direct current (DC) or alternating current (AC) arc discharges, or electromagnetic energy sources such as radio-frequency (RF) and microwave radiation. However, direct current thermal arc plasma remains the preferred technology for treating MSW, hazardous waste, industrial waste, and other difficult-to-treat materials because of its operational simplicity, high thermal efficiency, and ability to generate extremely high temperatures. The generation of thermal arc plasma is achieved using a plasma torch, which converts electrical energy into a highly concentrated plasma jet. A typical plasma torch consists of a cathode (negative electrode) and an anode (positive electrode) between which an electric arc is established [20]. The intense electrical discharge ionises the working gas within the arc chamber, producing a dense, high-temperature plasma. When the ionised gas is forced through the torch by a high-velocity gas stream, it emerges from the nozzle as a plasma jet capable of reaching temperatures of several thousand degrees Celsius. Owing to its extremely high temperature and energy density, the plasma jet is capable of rapidly decomposing complex waste materials into their fundamental molecular constituents.

Plasma torches are broadly classified into two categories according to the location of the arc: transferred arc torches and non-transferred arc torches. In a transferred arc plasma torch, one electrode is located within the torch body while the second electrode, usually the anode, is positioned externally and forms part of the material being treated or the reactor itself [27]. Consequently, the plasma arc is established outside the water-cooled torch body, enabling direct transfer of thermal energy to the feedstock. This configuration provides exceptionally high heating efficiencies, often exceeding 90%, and is therefore preferred for applications requiring intensive heat transfer, such as plasma melting, metallurgical processing, and plasma gasification. The relatively large inter-electrode distance, which may range from a few centimetres to approximately one metre, facilitates the generation of long, stable plasma arcs. The internal electrode may be fabricated from consumable materials such as graphite or from water-cooled metallic electrodes, whereas the external electrode is typically manufactured from highly conductive metals, including copper or silver, to ensure efficient heat dissipation and uniform plasma distribution.

In contrast, a non-transferred arc plasma torch contains both the cathode and anode within the water-cooled torch housing. During operation, an electric arc is established between these internal electrodes, generating

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a high-temperature plasma that is subsequently expelled through a nozzle by a pressurised gas stream to form a plasma jet [28]. Since the arc remains confined within the torch, heat is transferred indirectly to the material being processed. Although this configuration generally exhibits lower thermal efficiencies, typically between 50 and 75%, it offers several operational advantages, including lower power consumption, reduced electrode erosion, minimal vibration and noise, improved operational stability, and simplified reactor design. These characteristics have contributed to the widespread application of non-transferred arc plasma torches in industrial waste treatment systems, particularly where operational reliability and ease of maintenance are prioritised over maximum thermal efficiency.

Overall, the exceptional temperatures generated by TP torches, together with their ability to completely decompose organic materials and vitrify inorganic constituents, have established TP technology as one of the most effective thermochemical processes for the treatment of MSW, hazardous waste, biomedical waste, and other difficult-to-manage waste streams. Consequently, TP gasification continues to attract considerable research interest as a sustainable waste-to-energy technology capable of achieving high waste destruction efficiencies while simultaneously recovering valuable energy and material resources.

2.3 Thermal Plasma Gasification of Municipal Solid Waste

Thermal plasma pyrolysis, commonly referred to as plasma pyrolysis, is an allothermal thermochemical conversion process in which MSW is decomposed using an external plasma heat source under oxygen-deficient conditions. When a controlled quantity of oxygen, air, or steam is introduced into the plasma reactor, the process is transformed into plasma gasification (PG). Although both technologies utilise thermal plasma as the primary energy source, they differ principally in the presence of a gasifying agent, which promotes additional gasification reactions and enhances syngas production. During plasma gasification, the organic fraction of waste undergoes rapid thermal decomposition followed by gasification to produce synthesis gas (syngas), comprising predominantly carbon monoxide (CO) and hydrogen (H_2), together with smaller amounts of carbon dioxide (CO_2), water-vapour (H_2O), methane (CH_4), and other light hydrocarbons [29]. Owing to its high calorific value, syngas represents a valuable energy carrier that can be utilised directly for electricity generation, industrial heating, and the production of synthetic fuels, or further processed to produce high-purity hydrogen for fuel-cell applications.

Simultaneously, the inorganic constituents of the waste, including metals, glass, and mineral matter, are exposed to the extremely high temperatures generated by the plasma torch and are converted into molten products. Upon cooling, these materials solidify into chemically stable vitrified slag and metallic ingots [30]. The vitrified slag possesses favourable mechanical and chemical properties, making it suitable for potential use in road construction, concrete production, and other civil engineering applications. Likewise, the metallic ingots can be further processed to recover valuable metals, thereby contributing to resource recovery and the circular economy. Furthermore, the exceptionally high temperatures generated during plasma treatment ensure the almost complete destruction of hazardous organic compounds, pathogens, and toxic substances, converting them into simpler and environmentally benign products while substantially reducing the formation of secondary pollutants. PG has therefore become recognised as one of the most effective and environmentally sustainable thermochemical technologies for the treatment of MSW. The process involves a complex network of heterogeneous gas-solid reactions and homogeneous gas-phase reactions, as represented by Equations 1-8 [31]. The relative importance of these reactions depends primarily on the gasification temperature and the type of gasifying agent employed.

When oxygen is used as the gasifying agent, the elevated temperatures characteristic of PG promote oxidation and reduction reactions, particularly the Boudouard reaction (Equation 2) and the dry reforming reaction (Equation 6), both of which contribute significantly to carbon monoxide production and syngas quality. In contrast, when steam is employed as the gasifying agent, the water-gas reaction (Equation 3) and steam reforming reaction (Equation 5) become the dominant pathways, enhancing hydrogen production and increasing the H_2/CO ratio of the resulting syngas. Consequently, careful selection of the gasifying agent provides an effective means of controlling syngas composition according to its intended end use.

One of the principal advantages of PG over conventional gasification technologies is the production of virtually tar-free syngas. Tar compounds are thermally unstable at temperatures above approximately 1,100 ^{o}C and are therefore rapidly decomposed within the high-temperature plasma environment. These heavy hydrocarbons undergo secondary cracking and reforming reactions, producing additional carbon monoxide and hydrogen while preventing tar accumulation within downstream gas-cleaning and energy-conversion systems. The effective elimination of tar not only improves syngas quality but also enhances process efficiency, reduces maintenance requirements, and broadens the range of potential applications for the recovered synthesis gas.

Combustion of carbon: $$C + O_2 \rightarrow CO_2 \; (exothermic) \tag{1}$$

Boudouard reaction: $$C + CO_2 \rightarrow 2CO \; (endothermic) \tag{2}$$

Water-gas reaction: $$C + H_2O \rightarrow CO + H_2 \; (endothermic) \tag{3}$$

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Water-gas shift reaction: $CO + H_2O \rightarrow CO_2 + H_2\ (exothermic)$ (4)
Reforming reaction: $CH_4 + H_2O \rightarrow CO + 3H_2\ (endothermic)$ (5)
Dry reforming reaction: $CH_4 + CO_2 \rightarrow 2CO + 2H_2\ (endothermic)$ (6)
Molecular dissociation of water: $2H_2O \rightarrow 2H_2 + O_2\ (endothermic)$ (7)
Hydrogen-gasification: $C + 2H_2 \rightarrow CH_4\ (exothermic)$ (8)

2.4 Plasma Gasification of MSW and Hazardous Waste

The application of PG for waste treatment and resource recovery has attracted considerable research interest owing to its ability to process a wide range of waste streams while simultaneously recovering energy and valuable by-products. Numerous studies have demonstrated the technical feasibility of PG for the treatment of MSW, hazardous waste, biomedical waste, industrial residues, plastics, biomass, and other carbonaceous materials. Unlike conventional thermal treatment technologies, PG operates at extremely high temperatures, enabling almost complete decomposition of organic compounds into synthesis gas (syngas), primarily hydrogen (H_2) and carbon monoxide (CO), while converting inorganic constituents into an environmentally stable vitrified slag. Consequently, the technology has been widely recognised as an effective waste-to-energy approach capable of significantly reducing waste volume, minimising harmful emissions, and recovering valuable energy products. Earlier reviews by [32], [33], [34], [35], [36], [37], and [38] consistently highlighted the potential of PG as an advanced alternative to conventional waste treatment technologies.

Among the earliest comprehensive investigations, Mountouris *et al.* [32] evaluated PG as a sustainable treatment technology for complex MSW streams comprising plastics, paper, textiles, wood, food waste, rubber, and other combustible materials. Their findings demonstrated that the process produced a hydrogen- and carbon monoxide-rich syngas with minimal tar formation while substantially reducing waste volume. More importantly, hazardous constituents were immobilised within an inert vitrified slag, resulting in considerably lower pollutant emissions than those associated with conventional incineration. The authors concluded that PG represents a promising technology for sustainable waste management and energy recovery, although improvements in process efficiency and reductions in operational costs remain necessary before widespread commercial deployment can be achieved.

Further evidence supporting the viability of PG was presented by Lemmens *et al.* [33], who investigated the treatment of high-calorific refuse-derived fuel produced from carpet and textile waste. Their study confirmed that PG generated a stable, energy-rich syngas together with vitrified slag exhibiting acceptable leaching characteristics, thereby demonstrating its suitability as a secondary construction material. Nevertheless, operational limitations associated with the pilot-scale reactor prevented stable long-term operation and restricted comprehensive energy assessment. Consequently, the authors recommended further reactor optimisation, improved process control, enhanced gas-cleaning systems, and additional pilot-scale investigations to establish the environmental and commercial viability of the technology.

The performance of Plasma Gasification Melting (PGM) technology for MSW conversion was subsequently investigated by Zhang *et al.* [34]. Their work demonstrated that combining air and steam as gasifying agents produced syngas with a heating value of approximately 6-7 MJ/Nm^3 while achieving energy efficiencies approaching 60%. In addition to producing high-quality syngas, the process generated inert vitrified slag suitable for use as a construction material, thereby contributing to both waste reduction and resource recovery. The authors further recommended optimisation of the equivalence ratio, increased steam injection, and reduction of tar formation to improve overall process efficiency and facilitate industrial-scale implementation of PG technology.

Beyond electricity generation, several researchers have explored PG as a route for hydrogen production. Byun *et al.* [35] integrated a TP gasifier with water-gas shift and pressure swing adsorption units to recover hydrogen from paper mill waste. The integrated system successfully produced ultra-high-purity hydrogen exceeding 99.99% at a production rate of 20 Nm^3/h while achieving approximately 97% carbon conversion efficiency. Furthermore, atmospheric emissions remained well below regulatory limits, demonstrating both the environmental and technical feasibility of the process. The authors suggested that future research should focus on improving process stability, reducing production costs, scaling up the technology, and producing hydrogen of even higher purity for fuel-cell applications.

Similar outcomes were reported by Hlina *et al.* [36], who investigated argon/water PG of biomass and waste materials, including spruce sawdust, wood pellets, waste plastics, and tyre-derived pyrolysis oil. Their experimental results revealed that the generated syngas contained approximately 90% hydrogen and carbon monoxide with negligible tar formation, while carbon conversion efficiencies ranged between 80% and 100%, closely matching theoretical predictions. However, the process required substantial electrical energy, particularly during the gasification of pyrolysis oil. Despite this limitation, the authors concluded that PG remains a promising approach for producing clean syngas from biomass and waste, especially where complete waste destruction and high-quality gas production are required.

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Recent investigations have extended PG to the conversion of liquid waste streams. Tamošiūnas *et al.* [39] demonstrated that thermal arc PG of waste cooking oil using steam produced hydrogen-rich syngas with an optimum steam-to-oil ratio of 2.33, resulting in hydrogen and carbon monoxide concentrations of 47.9% and 22.42%, respectively, together with an energy conversion efficiency of 85.42%. In a related study, Tamošiūnas *et al.* [40] investigated the PG of waste glycerol generated during biodiesel production. Their results showed that water-vapour plasma significantly outperformed air plasma, achieving complete waste conversion, high syngas concentration, an H_2/CO ratio of approximately 2.07, and an energy conversion efficiency of 63.86%. These findings demonstrate the versatility of PG for converting diverse liquid wastes into valuable synthesis gas while highlighting the importance of steam-assisted plasma systems for improving process performance.

PG has also proven highly effective for plastic waste valorisation. Mączka *et al.* [41] investigated plasma pyrolysis of polyethylene waste and reported the production of combustible gases rich in hydrogen, methane, and carbon monoxide, together with liquid hydrocarbons ranging from C_{10} to C_{33}. The liquid products possessed fuel characteristics comparable to diesel fuel, although they were considered more suitable for heating applications or as chemical feedstocks. In addition, the process generated significantly lower aromatic compounds and pollutant emissions than conventional incineration. These findings further reinforce the environmental advantages of plasma-based waste conversion technologies while emphasising the need for optimisation of operating conditions and reactor design before commercial implementation.

In addition to MSW, PG has demonstrated considerable potential for the treatment of hazardous industrial wastes. Moustakas *et al.* [37] reported that PG coupled with vitrification effectively converted hazardous industrial waste into combustible syngas and environmentally inert slag while achieving lower atmospheric emissions and reduced slag toxicity than conventional thermal treatment technologies. The process also enabled substantial waste volume reduction and recovery of reusable construction materials from vitrified products, thereby contributing to both environmental protection and resource conservation. Similarly, Paulino *et al.* [38] evaluated PG of biomedical waste integrated with an internal combustion engine for electricity generation. Although the plasma gasifier achieved an energy efficiency of approximately 78.6%, the overall gasifier-engine system attained a lower efficiency of 15.7% owing to the substantial electricity demand of the plasma torch. Nevertheless, economic assessment indicated a favourable payback period of four to six years under suitable operating conditions, suggesting that PG offers considerable long-term potential for sustainable biomedical waste management and energy recovery.

Collectively, these experimental investigations demonstrate that PG is a technically feasible and environmentally sustainable technology capable of treating diverse waste streams while producing valuable syngas and inert vitrified slag. Despite the consistently reported advantages of high waste destruction efficiency, low emissions, and resource recovery, most studies identified high electrical energy consumption and operational costs as the principal barriers to large-scale commercial deployment. Consequently, continued efforts towards reactor optimisation, improved energy integration, enhanced syngas cleaning, and process scale-up remain essential for improving the economic competitiveness of PG technology.

2.5 Modelling, Simulation and Optimisation of PG Processes

While experimental investigations have established the technical feasibility of PG for treating a wide variety of waste streams, large-scale commercial deployment remains constrained by the high capital investment and electrical energy requirements associated with plasma systems. Consequently, considerable research has focused on modelling, simulation, and process optimisation to improve reactor performance, maximise syngas production, reduce energy consumption, and enhance the overall economic viability of PG technology. Computational modelling has become an indispensable tool for predicting reactor behaviour, evaluating operating conditions, and designing efficient PG systems before pilot- or industrial-scale implementation.

Several studies have demonstrated the flexibility of PG for treating multiple waste streams simultaneously. Fabry *et al.* [42] examined the gasification of MSW, hazardous waste, medical waste, biomass, used tyres, plastics, heavy oil, and refuse-derived fuel using TP technology. Their review established that the extremely high operating temperatures promoted almost complete decomposition of organic materials, resulting in cleaner syngas with significantly lower tar concentrations than those produced by conventional gasification systems. The process also generated higher hydrogen and carbon monoxide yields while accommodating heterogeneous feedstocks that are difficult to process using conventional thermal technologies. The authors therefore advocated continued industrial development, optimisation of plasma reactors, and improvements in syngas purification to facilitate commercial deployment.

A similar conclusion was reached by Nicolae [43], who demonstrated that PG can simultaneously process MSW, hazardous industrial waste, hospital waste, sewage sludge, waste oils, solvents, and used tyres. The study showed that the organic fraction of these wastes is efficiently converted into synthesis gas suitable for electricity generation, hydrogen production, and liquid biofuel synthesis, whereas the inorganic fraction is transformed into environmentally stable vitrified slag suitable for construction applications. Consequently, landfill disposal can be reduced to less than 5%, accompanied by substantial reductions in greenhouse gas emissions compared with

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conventional incineration. These findings further reinforce the versatility of PG as a comprehensive waste management and resource recovery technology.

To better understand the influence of operating parameters on process performance, numerous researchers have developed thermodynamic and process simulation models using Aspen Plus. These models have enabled systematic evaluation of operating conditions while significantly reducing the time and cost associated with experimental investigations. Indrawan *et al.* [44] developed an Aspen Plus model to investigate low-temperature PG of MSW operating between 1,500 and 2,500 ^{o}C. Their results demonstrated that reducing plasma temperature substantially lowered plasma torch energy consumption while maintaining satisfactory hydrogen and carbon monoxide production. Nevertheless, overall process efficiency remained lower than that achieved by conventional gasification because of the electrical energy required to sustain the plasma arc. The authors therefore recommended optimisation of plasma gas flow rates and operating conditions to improve overall process efficiency and commercial competitiveness.

Using a similar modelling approach, Tavares *et al.* [45] evaluated the influence of gasification temperature, equivalence ratio, steam-to-feedstock ratio, and different gasifying agents on PG performance. Their validated Aspen Plus model demonstrated that steam produced the highest hydrogen concentration, whereas oxygen generated syngas with the highest carbon monoxide concentration and the greatest lower heating value (LHV). Furthermore, the extremely high temperatures associated with PG virtually eliminated tar formation, thereby improving syngas quality. The study concluded that optimum operating conditions depend largely on the intended application of the produced syngas and recommended integrating techno-economic assessments into future optimisation studies.

Comparable findings were reported by Munir *et al.* [46] and Zitouni-Petrogianni and Voutsas [47], both of whom employed Aspen Plus simulations to investigate low-temperature PG of MSW. Their studies consistently demonstrated that reducing plasma operating temperature significantly decreases electricity consumption while maintaining acceptable syngas quality. However, they also emphasised that further optimisation of plasma gas flow rates, reactor operating conditions, and energy integration strategies is essential to overcome the economic limitations associated with PG technology.

The influence of feedstock composition has also received considerable attention. Mazzoni and Janajreh [48] investigated plasma co-gasification of MSW and plastic solid waste using an Integrated Plasma Gasification Combined Cycle (IPGCC) model. Their results demonstrated that oxygen-enriched plasma substantially enhanced syngas production and energy recovery, with the highest plant efficiency of approximately 38% being achieved using a feedstock blend containing 70% MSW and 30% plastic waste. Although steam addition increased hydrogen production, it simultaneously reduced electrical efficiency, highlighting the trade-off between syngas composition and overall plant performance. The authors therefore recommended optimisation of feedstock blending and gasifying agent selection to maximise energy recovery.

Earlier modelling work by Janajreh *et al.* [49] compared PG with conventional air gasification for a diverse range of feedstocks, including MSW, waste tyres, coal, algae, treated and untreated wood, plywood, and pine needles. Although PG consistently produced higher-quality hydrogen-rich syngas and effectively vitrified inorganic residues, the average process efficiency remained lower than that of conventional air gasification owing to the substantial electrical energy consumed by the plasma torch. The authors therefore suggested that PG should primarily be employed for hazardous waste destruction and specialised waste treatment applications where its superior environmental performance outweighs its higher operating costs.

The reliability of simulation models has been further demonstrated through comparison with experimental investigations. Messerle *et al.* [50] combined thermodynamic modelling with experimental validation to evaluate PG of biomedical waste. Excellent agreement between simulated and experimental results confirmed the capability of PG to produce high-calorific syngas while completely destroying hazardous compounds, including pathogens, dioxins, and furans. Furthermore, no harmful contaminants were detected in the vitrified slag, confirming the environmental advantages of PG over conventional incineration technologies. Overall, modelling and simulation studies have significantly improved understanding of PG processes by identifying the operating parameters that most strongly influence syngas quality, energy efficiency, and reactor performance. Collectively, these investigations demonstrate that optimisation of plasma temperature, equivalence ratio, steam addition, plasma gas flow rate, feedstock composition, and gasifying agent selection can substantially enhance process performance. Nevertheless, high electrical energy consumption remains the principal obstacle to widespread commercial implementation. Future research should therefore integrate advanced reactor design, process intensification, renewable electricity sources, and comprehensive techno-economic optimisation to improve the competitiveness of PG as a sustainable waste-to-energy technology.

2.6 Operating Parameters, Thermodynamic Performance and Commercialisation of PG

Although numerous experimental and modelling studies have demonstrated the technical feasibility of PG, its widespread commercial adoption depends largely on optimising operating parameters, improving

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thermodynamic performance, and demonstrating long-term economic viability. Consequently, many researchers have investigated the influence of reactor design, plasma generation techniques, gasifying agents, feedstock characteristics, and process integration on syngas production, energy efficiency, and overall system performance. Collectively, these studies provide valuable insights into the factors governing PG while identifying strategies for improving process efficiency and reducing operating costs.

One of the most comprehensive reviews of process optimisation was presented by Sanlisoy and Carpinlioglu [51], who evaluated the influence of different plasma generation systems, including direct current (DC), radio-frequency (RF), and microwave plasma technologies, together with various reactor configurations. Their review demonstrated that higher plasma power generally enhances feedstock conversion and syngas production, whereas appropriate steam addition promotes hydrogen formation through steam reforming and water-gas shift reactions. Feedstock properties, particularly moisture content, particle size, and chemical composition, were also shown to exert significant influence on gasification efficiency. Furthermore, microwave plasma systems were identified as particularly promising because of their superior energy transfer characteristics and higher conversion efficiencies. The authors concluded that further experimental validation and the development of standardised thermodynamic models are necessary to accelerate commercial implementation of PG technology.

The importance of process optimisation was similarly emphasised by Pourali [52], who described PG as a cleaner alternative to conventional waste-to-energy technologies. The study highlighted the technology's capability to convert MSW into valuable synthesis gas while producing inert vitrified slag and recoverable metals. Nevertheless, the author recognised that high capital investment, limited operational experience, the absence of universally accepted technical standards, and public concerns regarding emerging waste-treatment technologies continue to impede large-scale commercial deployment. Consequently, the study recommended stronger regulatory frameworks, certification of plasma treatment facilities and vitrified products, expansion of pilot-scale projects, and increased governmental support to facilitate technology commercialisation.

A broader assessment of plasma-based waste conversion technologies was presented by Tang *et al.* [53], who reviewed the development of plasma pyrolysis and PG systems for sustainable waste management. Their review confirmed that plasma technologies achieve rapid decomposition of complex waste streams, substantial reductions in waste volume, and high-quality syngas production with lower environmental impacts than conventional thermal treatment processes. Among the reactor designs evaluated, plasma spout-fluidised bed reactors exhibited superior heat and mass transfer characteristics, resulting in enhanced reaction kinetics and improved gasification efficiency. The authors therefore recommended continued optimisation of reactor configurations, increased utilisation of steam-assisted plasma systems, and further industrial-scale investigations to overcome the remaining technical and economic barriers to commercial implementation.

Thermodynamic analyses have further enhanced understanding of PG performance. Popov *et al.* [54] investigated PG of wood waste and demonstrated that air-plasma systems significantly increased the chemical energy content of the produced syngas while experimental observations closely agreed with theoretical predictions. Likewise, Zhang *et al.* [55] evaluated the thermodynamic performance of PGM through detailed energy and exergy analyses. Their study reported overall energy and exergy efficiencies exceeding 90% when the energy contained in tar was included in the assessment. However, the efficiency of clean syngas production was considerably lower because of substantial tar formation, emphasising the importance of process optimisation and effective gas-cleaning technologies. The authors recommended moderate steam injection together with optimisation of plasma power and air supply to maximise both energy recovery and exergy efficiency while minimising performance losses.

The integration of PG with advanced energy conversion technologies has also attracted significant research interest as a means of improving overall plant efficiency. Galeno *et al.* [56] evaluated an Integrated Plasma Gasification/Fuel Cell (IPGFC) system employing refuse-derived fuel as the feedstock. Their analysis demonstrated that coupling PG with a solid oxide fuel cell substantially improved electrical efficiency compared with conventional waste incineration while producing cleaner synthesis gas suitable for high-efficiency power generation. These findings suggest that hybrid energy systems may provide an effective pathway for improving the economic performance of PG plants and enhancing the utilisation of recovered energy.

Recent investigations have further demonstrated the adaptability of PG to specialised waste streams. Erdogan and Yilmazoglu [57] investigated medical waste gasification using numerical simulation and reported that feedstocks with higher moisture contents produced hydrogen-rich syngas when operated at an optimum equivalence ratio of 0.1. Similarly, Mazzoni *et al.* [58] examined the co-gasification of MSW with petroleum hazardous waste generated by the oil and gas industry. Their simulation results showed that introducing a relatively small proportion of hazardous waste into MSW significantly improved electricity generation while maintaining acceptable plant efficiency. These studies illustrate the flexibility of PG for processing heterogeneous waste mixtures without compromising environmental performance.

Very little literature is available on the plasma gasification (PG) of petroleum oily sludge. One of the few reported studies was conducted by Ali *et al.* [29], who investigated the application of thermal plasma for the treatment of petroleum sludge. The sludge was characterised by high moisture content (78.91%), low volatile

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matter (5.52%), low fixed carbon (10.51%), and a total organic carbon (TOC) content of 54.48%, with hydrocarbons constituting the major organic fraction. The thermal plasma process achieved substantial waste reduction, with mass and volume reductions of 36.87–91.40% and 59.59–94.52%, respectively, together with a maximum TOC reduction of 93.76%. The treatment produced an inert vitrified solid residue and a hydrogen-rich syngas, demonstrating the effectiveness of the technology in both waste stabilisation and energy recovery. The authors concluded that thermal plasma is a promising and sustainable option for petroleum sludge management, offering additional benefits through metal recovery, syngas utilisation for energy generation, and the reuse of the vitrified residue as a construction material.

In another investigation, Ali *et al.* [59] optimised the thermal plasma gasification of petroleum oily sludge using response surface methodology (RSM). The developed models accurately predicted the optimum cold gas efficiency (52.59%) and the CO/CO_2 ratio (1.79), with optimum conditions of 188.15 A plasma current, 31.54 L/min gas flow, and 1.89 min treatment time. The authors recommend RSM as an effective tool for optimising plasma gasification processes to maximise syngas quality and energy recovery while improving treatment efficiency.

Beyond technical performance, the long-term sustainability of PG depends on its economic competitiveness. Ramos *et al.* [60] evaluated the economic and socioeconomic viability of PG of MSW using a life-cycle costing approach. Their findings demonstrated that the technology becomes economically attractive when both electricity and vitrified slag are commercialised, thereby reducing overall waste treatment costs while improving environmental sustainability. The authors further highlighted the importance of government incentives, including renewable energy subsidies and fiscal support, together with strategic plant siting and reliable feedstock supply chains to enhance project viability. Similarly, Dodge [61] concluded that although PG requires substantial initial capital investment, its multiple revenue streams (including electricity generation, syngas utilisation, recyclable metals, and vitrified construction materials) provide significant opportunities for long-term economic sustainability when supported by appropriate policy and regulatory frameworks.

In addition to direct waste treatment, TP technology has proven highly effective for the management of secondary residues generated by conventional incineration processes. Abdulkarim *et al.* [10] demonstrated that TP treatment effectively vitrifies MSW incineration residues, including bottom ash, fly ash, and air pollution control residues containing hazardous heavy metals, dioxins, and furans. The resulting vitrified products exhibited excellent chemical stability and potential for reuse in construction materials, glass-ceramics, geopolymers, and road engineering applications. Likewise, Ali *et al.* [25] reported that plasma vitrification of incinerator fly ash and bottom ash reduced waste volume by approximately 90%, immobilised hazardous heavy metals, and produced stable glassy materials suitable for beneficial reuse. These studies demonstrate that TP technology contributes not only to waste destruction but also to resource recovery and the development of circular economy pathways through the valorisation of treatment residues.

Overall, the literature demonstrates that PG is an advanced and versatile waste treatment technology capable of converting a broad spectrum of municipal, industrial, hazardous, biomedical, and petroleum-derived wastes into valuable energy products while producing environmentally stable vitrified residues. Experimental investigations have consistently confirmed high waste destruction efficiencies, low pollutant emissions, and excellent syngas quality, whereas modelling and thermodynamic studies have identified the operating conditions required to maximise process performance. Furthermore, techno-economic analyses indicate that PG can become commercially viable when integrated with efficient energy recovery systems and supported by favourable policy measures. Despite these advances, high electricity consumption, capital-intensive infrastructure, limited full-scale operational experience, and the need for further optimisation continue to constrain widespread commercial implementation.

3.0 Variability and differences in reported results

The apparently different results reported in the literature do not necessarily represent contradictions, but rather reflect differences in feedstock characteristics, reactor configuration, plasma technology, operating conditions, gasifying agents, system boundaries and performance definitions. For instance, reported energy efficiencies very considerable because some studies evaluate the plasma gasifier alone, whereas others include plasma electricity consumption and downstream energy-conversion units. Similarly, differences in syngas composition arise from variations in gasifying agent, equivalent ratio, steam-to-feedstock ratio, reactor prevailing temperature and feedstock composition. Results from thermodynamics and Aspen Plus models may also differ from experimental results because models commonly employ equilibrium assumptions and simplified reaction mechanisms that do not fully account for heat losses, mixing limitations, kinetic effects and non-uniform reactor conditions. Differences in tar results may additionally arise from variations in temperature, residence time, reactor design, and nature of feedstock and tar measurement procedures. Therefore, reported PG performance should be compared only when the feedstock, operating conditions, efficiency definitions and system boundary are

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sufficiently similar. Table 3 presents the variability in the reported results and highlights the major areas of discrepancy identified in the review, together with the possible reasons for these variations.

Table 3: Major areas where result differ

	Area	**Variation in reported results in the review**	**Highlights on the discrepancies**
1	Energy/process efficiency	Zheng *et al.* [34] reported energy efficiency approaching 60%, while Janajreh *et al.* [49] found that PG had lower average efficiency than conventional air gasification. Paulimo *et al.* [38] reported 78.6% efficiency for the plasma gasifier, but only 15.7% for the integrated gasifier-engine system	The studies use different definitions/system boundaries for efficiency. Some evaluate only the gasifier, while others include plasma electricity consumption and downstream equipment. Feedstock, plasma power, gasifying agent, and energy recovery system also differ
2	Tar formation	Much of the review state that PG produces virtually tar-free syngas because of very-high temperature. However, Zhang *et al.* [55] reported substantial tar formation, with clean-syngas efficiency considerable lower than the overall energy/exergy efficiency.	Plasma temperature alone does not determine tar formation. Reactor temperature distribution, residence time, feedstock, steam/ air ratio, plasma power and sampling/ measurement methods influence tar destruction. Importantly, Zhang *et al.* [55] reported efficiency included the energy contained in tar, which makes it different from clean-syngas efficiency.
3	Effect of gasifying agent	Tavares *et al.* [45] found that steam produced the highest H_2 concentration, while oxygen produced the highest CO concentration and LHV. Mazzoni and Janajreh [48] similarly found that steam increased H_2 but reduced electrical efficiency.	Steam promotes water-gas and steam-reforming reactions, favouring H_2 formation, whereas oxygen promotes oxidation/reduction reactions and CO formation. Increasing steam also requires additional energy for heating/ vaporisation and can therefore reduce net electrical efficiency.
4	Effect of plasma temperature	Indrawan *et al.* [44], Munir *et al.* [46] and Zitouni-Petrogianni and Vautsas [47] found that reducing plasma temperature substantially reduces electricity consumption while maintaining acceptable syngas quality. Other studies emphasise the benefits of extremely high temperature for conversion and tar destruction.	The optimum temperature is a compromise. Higher temperature improves conversion and cracking but dramatically increases plasma power demand. The optimum therefore depends on the waste type and the desire product rather than being a single universal temperature.
5	Syngas composition	Byun *et al.* [35] obtained > 99.99% pure H_2 after integrating water-gas shift and pressure-swing adsorption. Hlina *et al.* [36] reported syngas containing approximately 90% H_2 +CO. Tamošiūnas *et al.* [39] obtained 47.9% H_2 and 22.42% CO from waste cooking oil.	These are not directly comparable products. Byun's value is purified hydrogen after downstream separation, whereas Hlina and Tamošiūnas report raw or relatively untreated syngas composition. Feedstocks and gasifying agents also differ substantially.
6	Carbon conversion efficiency	Byun *et al.* [35] reported approximately 97% carbon conversion, whereas Hlina *et al* [36] reported 80-100%, depending on the material.	Different feedstocks have different carbon structures and reactivities. Moisture, volatile matter, fixed carbon, temperature, residence time and gasifying-agent flowrate all affect conversion.
7	Effect of feedstock composition	Mazzoni and Janajreh [48] found the highest plant efficiency (~38%) with 70% MSW+30% plastic waste. Other studies considered biomass, waste tyres, paper, medical waste, oils and hazardous wastes and obtained different performance levels.	MSW is inherently heterogeneous. Plastic has a high calorific value, while organic MSW can obtain substantial moisture and inert material. Consequently, different waste blends change heating value, moisture content, ash content, H_2/CO ratio and energy requirements.

	Area	Variation in reported results in the review	Highlights on the discrepancies
8	Plasma technology/ reactor configuration	Sanlisoy and Carpinlioglu [51] considered DC, RF and microwave plasma and found microwave systems particularly promising. Tang *et al.* [53] reported superior heat/mass transfer and gasification performance for plasma spout-fluidised-bed reactors.	Different plasma sources transfer energy to the feedstock differently. Reactor geometry, heat transfer, residence time and mixing also influence conversion and syngas production. Therefore, result from one reactor cannot automatically be generalised to another.
9	Experimental versus modelling results	Messerle *et al.* [50] found excellent agreement between simulation and experiment, but the review also contains numerous Aspen Plus studies predicting performance under idealised conditions.	Thermodynamic models commonly assume equilibrium, ideal mixing and simplified reaction mechanisms. Real reactors experience heat losses, incomplete mixing, electrode losses, kinetic limitations and non-uniform temperature fields. Thus, simulation can give different results from experiments.
10	Economic viability	Ramos *et al.* [60] concluded that PG becomes economically attractive when electricity and vitrified slag are commercialised, whereas other researchers identify high capital and electricity costs as major barriers.	Economic conclusions depend strongly on electricity prices, plant scale, feedstock availability, disposal costs, and value of recovered energy/materials, government incentives and the assumed lifetime of the plant.

4.0 Conclusion

The continuous increase in MSW generation, driven by rapid population growth, urbanisation, industrialisation, and changing consumption patterns, has intensified the need for sustainable and efficient waste management technologies. Conventional disposal methods, particularly landfilling, are increasingly constrained by limited land availability, greenhouse gas emissions, leachate generation, and associated environmental and public health concerns. Consequently, thermochemical waste conversion technologies have emerged as attractive alternatives because they not only minimise the volume of waste requiring final disposal but also recover valuable energy and materials. This review has examined the major thermochemical treatment technologies employed for MSW management, namely incineration, pyrolysis, gasification, plasma gasification, and HTC. Each technology possesses distinct operating principles, advantages, and limitations. Incineration remains the most established technology for large-scale waste treatment; however, concerns regarding atmospheric emissions, ash management, and relatively lower resource recovery have encouraged the development of more advanced alternatives. Pyrolysis and conventional gasification provide improved opportunities for recovering valuable fuels and chemicals but are generally limited by feedstock variability, tar formation, and the need for extensive gas-cleaning systems. HTC offers an effective treatment option for wet biodegradable wastes but has relatively limited applicability to heterogeneous MSW streams.

Among these technologies, PG has emerged as one of the most promising advanced waste-to-energy technologies because of its ability to operate at extremely high temperatures, resulting in the almost complete destruction of organic materials and hazardous compounds. The technology simultaneously converts the organic fraction of waste into a hydrogen- and carbon monoxide-rich synthesis gas while transforming inorganic constituents into environmentally stable vitrified slag with potential applications in the construction industry. The exceptionally high operating temperatures suppress the formation of tar, dioxins, and furans, thereby producing cleaner syngas and reducing secondary pollution compared with conventional thermal treatment technologies. The review has also highlighted the fundamental characteristics of thermal plasma, the principles of plasma torch operation, and the distinctions between transferred and non-transferred arc plasma systems. Thermal plasma torches provide the extremely high heat flux and energy density required for efficient waste destruction and syngas production, making them particularly suitable for treating heterogeneous MSW, hazardous industrial wastes, biomedical waste, plastics, petroleum-derived residues, and other difficult-to-manage waste streams.

A comprehensive evaluation of published experimental studies demonstrates that PG consistently achieves high waste destruction efficiencies, substantial reductions in waste volume, low pollutant emissions, and the production of high-quality syngas suitable for electricity generation, hydrogen production, and synthetic fuel manufacture. Furthermore, the vitrified slag produced during the process exhibits excellent chemical stability and offers opportunities for beneficial reuse, thereby supporting the principles of sustainable resource management and the circular economy. The review further demonstrates that computational modelling and process simulation have become indispensable tools for understanding and optimising PG systems. Thermodynamic analyses and process simulations have improved understanding of the influence of operating parameters, including plasma

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temperature, equivalence ratio, steam-to-feedstock ratio, gasifying agent, plasma gas flow rate, and feedstock composition, on syngas quality, energy efficiency, and reactor performance. These studies have shown that careful optimisation of operating conditions can significantly enhance hydrogen production, improve overall energy recovery, and reduce operational costs while maintaining high waste conversion efficiencies.

Despite these considerable technical advantages, several challenges continue to limit the widespread commercial deployment of plasma gasification. The technology remains capital intensive and requires substantial electrical energy to sustain plasma generation. In addition, reactor design, electrode durability, process control, and long-term operational reliability require further improvement to enhance economic competitiveness. The limited number of large-scale commercial installations also indicates the need for additional pilot-scale demonstrations and long-term operational assessments under realistic industrial conditions. An important observation emerging from this review is that although extensive research has been conducted on the PG of MSW, biomass, plastics, biomedical waste, and other hazardous wastes, comparatively few studies have focused on petroleum oily sludge and related refinery wastes. Furthermore, relatively limited attention has been given to integrating feedstock characterisation, plasma gasification, product characterisation, environmental performance evaluation, process optimisation, and techno-economic assessment within a single comprehensive investigation. Addressing these research gaps is essential for advancing the practical application of PG to complex industrial waste streams and improving the sustainability of refinery waste management.

Future research should therefore focus on the development of energy-efficient plasma torches, advanced reactor designs, hybrid PG systems integrated with renewable energy sources, artificial intelligence-assisted process optimisation, and comprehensive life-cycle and techno-economic assessments. Greater emphasis should also be placed on full-scale demonstration projects, long-term operational performance, syngas purification technologies, carbon capture integration, and the beneficial utilisation of vitrified slag. These developments will improve process efficiency, reduce operational costs, and enhance the commercial viability of plasma gasification. Overall, PG represents one of the most advanced thermochemical technologies currently available for sustainable MSW treatment and resource recovery. Its unique capability to simultaneously achieve high waste destruction efficiency, produce clean synthesis gas, recover valuable materials, and minimise environmental pollution positions it as a key technology for future integrated waste management systems. Continued advances in reactor engineering, process optimisation, energy integration, and economic performance are expected to accelerate its transition from a promising emerging technology to a commercially viable solution for sustainable waste-to-energy conversion and circular resource utilisation.

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