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Plasma Gasification for Waste Management: Critical Insights into Thermodynamics, Technological Progress, and Socio-Economic Relevance

Nifa Thaslim. M*, Sulfath. H*, Mrs. BeenaKumari I P*

**B. Tech Student, Department of Civil Engineering, Ahalia School of Engineering and Technology, Palakkad, 678557*
**B. Tech Student, Department of Civil Engineering, Ahalia School of Engineering and Technology, Palakkad, 678557*
***Assistant Professor, Department of Civil Engineering, Ahalia School of Engineering and Technology, Palakkad, 678557*

A B S T R A C T

Over 2 billion tonesof municipal solid waste (MSW) per year requires a paradigm shift away from the conventional linear waste disposal and towards circular systems with a focus on recovery of resources. In this paper, we critically examine plasma gasification (PG) as a game-changing new approach to sustainable waste management. In addition to explaining the process, we delve into the plasma physics, thermodynamics, and reaction kinetics that determine syngas yield and quality. Central system components—torch design, refractory materials, and multi-stage gas cleaning systems—are assessed and contrasted against conventional thermal technologies such as incineration and pyrolysis.We advocate a multi-parameter assessment approach that combines Cold Gas Efficiency (CGE) and Carbon Conversion Efficiency (CCE) with total environmental Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA). While PG has appealing advantages, including near-total waste destruction, minimized emissions, and marketable byproducts of vitrified slag and syngas, these have to be balanced against capital costs that are high, process complexity, and acceptability problems. Pune and Vizag, India-based case studies offer a view of real-world implementation and limitations.Our assessment identifies that although PG enjoys robust thermodynamic and environmental merits, widespread adoption is constrained by economic, regulatory, and infrastructural limitations. We suggest a research agenda for catalytic advancement, integration of hybrid systems, material life, and new policy and funding mechanisms to close the viability gap and render PG feasible in a circular economy.

Keywords: Plasma Gasification, MSW, Circular Economy, Syngas, Thermodynamics, CGE, CCE, LCA, TEA, Incineration, Pyrolysis, Pune, Vizag, Hybrid Systems, Waste Valorization

1. Introduction

Anthropogenic Waste Footprint: A Quantitative Crisis

Modern-day waste production is a direct reflection of unsustainable world material consumption in the linear economy. The generation of municipal solid waste (MSW) is estimated to be more than 2.01 billion tones annually and projected to decrease significantly by only 70% to 3.40 billion tones by the year 2050, far surpassing the growth of population. Such a flood is a gargantuan multi-media environmental catastrophe: landfills are the third-largest source of anthropogenic methane (CH_4), a 28-34times more potent per century greenhouse gas; leachates from decomposing trash contaminate groundwater aquifers; and uncontrolled burning and inefficient incineration are significant sources of outdoor air pollution, with emissions of particulate matter (PM2.5, PM10), black carbon, and toxic compounds. Economic effects are equally massive, such as increasing expenses for disposing and collecting waste, externalized public health effects from diseases and cancers related to air pollution, loss of tourism revenues from the degraded environment, and cleanup of contaminated sites.

1.1 Systemic Failures of Linearity: Landfilling, Incineration, and the Recycling

The most popular technique worldwide is landfilling, which is really just a way to store waste. There is a limited amount of space, and even contemporary sanitary landfills present long-term hazards. Leachate needs constant treatment, which results in a long-term financial and environmental burden, and gas capture is only 60–85% effective, leaving fugitive methane emissions.Thermodynamics and chemistry limit incineration (waste-to-energy), which reduces volume by about 90%. Large CO_2 emissions, nitrogen oxides, and the possibility of incomplete burning are all produced during combustion, which also releases harmful pollutants like furans and dioxins. Residues are still an issue; hazardous fly ash frequently needs to be disposed of in a secure landfill, and bottom ash needs to be treated.Composting and recycling are essential but limited. Recovery rates are kept low

(<35%) due to market volatility, contamination in single-stream systems, and the technical limitations of recycling complex materials. A sizable portion of residual waste still needs to be disposed of.

1.2 The Paradigm of Advanced Conversion: Synthesis of Resources from Waste Disposal

To respond to these constraints, Advanced Thermal Treatment (ATT) technologies have been developed that seek to go beyond the capability of simple disposal by transforming the waste into useful products. Gasification and pyrolysis embody this new way of thinking. They are not incineration processes; they rather thermochemically transform carbon-containing materials in a deficiency of oxygen into a synthetic gas (syngas) and solid residues. Plasma gasification is at the pinnacle of this technological state. It uses the high, controllable temperature of a plasma arc (4,000–7,000°C) to not just gasify but to dissociate waste materials to their elemental form in a vessel referred to as a plasma converter, prior to re-forming them into a clean syngas and an inert, vitrified slag. It is a molecular dissociation and re-synthesis process, with the potential for ultimate destruction of waste and optimal resource recovery.

1.3 Review Scope and Novelty

This review seeks to be a thorough and critical review of plasma gasification technology, setting it apart from earlier writings by:

Going in-depth into the plasma physics, reactor engineering, and process chemistry that form the basis of PG, which makes it different from other thermal technologies.

Presenting an evidence-based, balanced view of its major strengths against its usually underrated systemic issues, notably economic viability.

Inclusion of a discussion on recent tools of assessment such as Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) to assess its overall performance.

Grounding theory in real-world advice based on global case studies with both successes and failures.

Suggesting an actionable, forward-looking research and policy agenda for overcoming main barriers and spurring future uptake.

2. The Science of Plasma: From Physics to Application

2.1Plasma State Fundamentals

Plasma is the fourth form of matter, different from solid, liquid, and gas. It is defined as a quasineutral gas of charged and uncharged particles with collective behavior. It is formed when a gas is heated to the point where the kinetic energy in the collision removes electrons from their atomic nuclei, leaving a broth of positive ions, free electrons, and neutral atoms. This ionized form is extremely electrically conductive and sensitive to electromagnetic fields. In thermal plasma uses such as PG, the level of ionization is extremely high (near 100%), and the temperatures are commonly well above 4,000°C—far higher than needed to dissociate any known chemical bond (e.g., C-C ~347 kJ/mol, C-H ~414 kJ/mol) and melt any inorganic substance.

2.2 Torch Technology: The Heart of the System

The plasma torch (or plasma arc generator) is the technological core. Designs differ, each with compromises:

* DC Non-Transferred Arc Torches:The most universal design in waste applications. A cathode (usually made of hafnium or tungsten) and a concentric, water-cooled copper anode are positioned centrally within the torch body itself, with an electric arc being established between them. A plasma gas (e.g., air, nitrogen, argon, or steam) is driven through this electric arc, becoming highly heated and ionized, and exits the torch nozzle as a high-velocity, high-enthalpy plasma jet. This jet is then injected into the gasification chamber, supplying the required heat. Their benefit is operational stability and isolation from the reactive melt.

* DC Transferred Arc Torches: In this, the electrical circuit is closed by transferring the arc from the cathode of the torch to the molten slag bath within the reactor, which serves as the anode. Direct heating of the melt pool is thus achieved, greatly enhancing energy transfer efficiency for vitrification of inorganic materials. But this configuration is difficult to sustain a steady arc and causes more rapid erosion of the electrode due to direct exposure to corrosive melt.

* AC and Radio Frequency (RF) Torches: Alternative architectures that can minimize electrode erosion problems of DC systems. AC torches switch the anode and cathode functions, while RF torches utilize electromagnetic induction to create plasma without electrodes. But these tend to have greater system complexity, expense, and lesser power densities than DC torches.

3.Process Description: A Detailed System-Level Analysis

3.1 Pre-Treatment: The All Important First Step

The stability and efficiency of PG process are greatly influenced by the quality of feedstock. "As-received" MSW is too high in moisture and too heterogeneous for efficient operation and therefore requires aggressive pre-treatment.

*Mechanical Biological Treatment (MBT):It is a sophisticated, combined pre-processing method. MSW is initially shredded to an even size. It is then subjected to a sequence of mechanical separation units: ferrous metals are removed by magnets; non-ferrous metals are recovered by eddy current separators; light organics are separated from heavy inerts by air classifiers and trommel screens. The ensuing organic fraction may be transferred to anaerobic digestion (AD) or composting. The remaining dry, more homogeneous, and high-calorific value material is referred to as Refuse-Derived Fuel (RDF) or Solid Recovered Fuel (SRF). Utilizing RDF as feedstock for PG, instead of raw MSW, significantly enhances process control, syngas quality, and overall efficiency.

* Drying:Having high moisture content is unfavorable since evaporating water absorbs massive quantities of energy (latent heat of vaporization), reducing the net energy output. Pre-drying of the feedstock by utilizing low-grade waste heat from the syngas cooling loop is one of the important strategies to enhance the overall energy balance of the plant.

3.2 The Gasification Kinetics and Reactor Design

The gasification reactor is a high-temperature reactor whose design (shaft furnace, kiln, or fixed bed) affects heat transfer, residence time, and conversion efficiency. Within, the process takes place in zones: drying (100–200 °C) evaporates water, pyrolysis (200–600 °C) disintegrates organics into gases, tars, and char, gasification (600–1,500 °C) reverts char with gasifying agents to CO and H_2, and the plasma/melting zone (>2,000 °C) shatters residual tars and melts inorganics into slag. Agent selection influences syngas quality—air is economical but has low-energy, dilute gas; oxygen gives medium-grade syngas but is energy-intensive to separate; and steam increases hydrogen yield but is energy-hungry.

3.3State-of-the-Art Syngas Cleaning and Conditioning

The raw syngas leaving the gasifier is loaded with dust, soot, tars, acid gases, and water content, thus a cleaning system is needed prior to its utilization. It is first cooled in a quench system or waste heat boiler, and coarse particulates are separated out by cyclones. Tar elimination is done either through wet scrubbing, which condenses the tars into wastewater, or high-temperature thermal/catalytic cracking, which cracks tars into valuable syngas constituents. Acid gases like HCl, SO_2, and HF are removed by wet scrubbers with chemical liquids or dry scrubbers with powder sorbents. Last, fine particulate matter is removed by baghouses or ceramic filters, and activated carbon filters refine the gas by adsorbing trace impurities like mercury.

4. Chemistry and Thermodynamics: Modeling the Process

4.1Governing Reactions and Chemical Equilibrium

Plasma gasification involves numerous concurrent gas–gas and gas–solid reactions, which may be simulated by chemical equilibrium calculations minimizing Gibbs free energy to estimate the end syngas composition as a function of feedstock, gasifying agent, temperature, and pressure.

Key Equilibrium Reactions:

BoudouardReaction:$C + CO_2 \leftrightarrow 2CO$ ($\Delta H = +172$ kJ/mol). Endothermic, favored by high temperatures.

Water-Gas Reaction: $C + H_2O \leftrightarrow CO + H_2$ ($\Delta H = +131$ kJ/mol). Endothermic, the primary source of H_2.

Water-Gas Shift Reaction: $CO + H_2O \leftrightarrow CO_2 + H_2$ ($\Delta H = -41$ kJ/mol). Exothermic. Critical for adjusting the H_2:CO ratio for downstream synthesis; its equilibrium constant decreases with temperature, meaning lower temperatures favor more H_2 and CO_2.

Methanation:$CO + 3H_2 \leftrightarrow CH_4 + H_2O$ ($\Delta H = -206$ kJ/mol). Exothermic, favored at lower temperatures and high pressures.

4.2.The Unique Role of Plasma: Beyond Simple Heating

Plasma arc does not just produce heat—it forms a strongly reactive atmosphere with ions, free electrons, and excited species that behave as catalysts, reducing activation energy and allowing for novel reaction pathways. This permits plasma gasification to reach extremely high Destruction and Removal Efficiency (DRE > 99.9999%) on stable and toxic substances like PCBs, dioxins, and pesticides well above what's possible with conventional incineration.

5. Products: Characterization and Market Pathways

5.1Syngas Utilization and Valorization Pathways

The purified, conditioned syngas is a multifunctional energy carrier with several end uses that define the economic worth of the whole plant. It can be utilized directly for fueling engines, turbines, or boilers to produce electricity with an efficiency of approximately 30–40%. For more valuable applications, syngas can be subjected to chemical synthesis, like Fischer–Tropsch conversion to make synthetic diesel, waxes, and lubricants, methanol synthesis for chemicals and fuels, or hydrogen via the water-gas shift reaction followed by cleanup for use in refineries, ammonia plants, or fuel cells. Syngas also can be biologically fermented by microbes to create ethanol, acetic acid, and other biochemicals, or methanated to produce synthetic natural gas (SNG) for pipeline transmission. The hydrogen portion of syngas also can be utilized in the synthesis of ammonia for fertilizers, and syngas can be mixed with natural gas and used for industrial boilers or district heating.

5.2Vitrified Slag: From Waste to Product

The vitrified slag from plasma gasification is a co-product and not a waste, and its marketability is essential to the economics of the project. For safe application, it has to be chemically characterized as non-hazardous and inert by testing such as TCLP or SPLP, as the glassy matrix retains heavy metals and inhibits leaching. Its engineering significance as a construction aggregate is established through high compressive strength, superior abrasion resistance (LA test), and versatile particle size distribution through crushing and screening. Last but not least, certification by the concerned authorities (e.g., ASTM or EN standards) is required to allow for large-scale utilization in concrete, road base, asphalt mixes, or rock wool insulation.

5.3 Recovery of Reusable Metal

Metals (ferrous and non-ferrous) melt and form at the gasifier base. The heavier metals, by virtue of density differences, float off the lighter silicate-based slag and can be tapped off individually. These are high-quality recovered metals—clean, oxide-free, and uncontaminated—representing a high-value product that can be sold directly to metal recyclers, bypassing the energy-intensive primary metal production

6. Performance Evaluation: An Integrated Framework

6.1Technical Metrics

Cold Gas Efficiency (CGE) represents the percentage of feedstock energy that is preserved in the clean syngas (usually 60–80%), and Carbon Conversion Efficiency (CCE) quantifies the amount of feedstock carbon that goes into syngas instead of remaining as char or tar (usually >95–99% in plasma-based systems). Syngas Yield is the volume of syngas produced per unit mass of feedstock (Nm^3/tone), and the Net Energy Balance is the total useful energy produced (electricity and heat) minus internal energy used by torches, pumps, and other auxiliaries, with a positive balance being essential for economic and operational viability.

6.2Environmental Metrics: Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is the single authoritative means to assess plasma gasification (PG) cradle-to-grave environmental impact relative to other waste management alternatives using multiple impact categories including Global Warming Potential (GWP), net greenhouse gas emissions plus avoided emissions due to displaced grid electricity and virgin material, Human Toxicity Potential (cancer and non-cancer) from air and water releases, Acidification Potential due to SO_x and NO_x releases, Eutrophication Potential due to discharge of nutrients, and Resource Depletion (abiotic) due to fossil fuel, mineral, and metal consumption; most peer-reviewed LCAs find that PG systems, especially those incorporating slag and metal recovery, offer superior performance relative to landfilling and incineration, notably for GWP and toxicity mitigation.

6.3Economic Metrics: Techno-Economic Analysis (TEA)

Plasma gasification (PG) techno-economic analysis (TEA) points out that the technology has better waste destruction and valuable byproducts, but its economic feasibility is difficult because of very high CAPEX and OPEX. Capital expenses are dominated by sophisticated gas cleanup systems, plasma torches, and energy recovery equipment, whereas operating expenses are dominated by electrical usage, refractory and torch maintenance, and skilled labor needs. On the income side, PG projects are highly dependent on waste tip charges, electricity or steam sales, and secondary revenues from vitrified slag, metals, or chemical feedstocks. The energy or treatment cost levelized is then the determining factor, and economic viability generally depends on favorable policies (e.g., renewable energy credits, carbon offsets), low electricity tariffs, and fully established markets for byproducts, in the absence of which PG might not be competitive with traditional incineration or landfilling.

7. Advantages vs. Challenges: A Nuanced Balance

7.1 Advantages (Reinforced with Evidence)

Plasma gasification (PG) is the ultimate solution for refractory wastes as it is uniquely suited to annihilate hazardous, medical, pharmaceutical, and electronic wastes with unparalleled Destruction and Removal Efficiency (DRE > 99.9999%), providing it with a decisive edge over traditional incineration. Its intrinsic pollution control derives from the reducing (oxygen-deficient) environment within the gasifier that inhibits fuel-NO_x formation, and sulfur in the feed is primarily converted to removable H_2S rather than SO_x in flue gas, and the very high temperatures ensure total cracking of dioxin and furan precursors. The process realizes highest volume reduction and landfill diversion, reducing waste volume by 95–99%, thus prolonging landfill lives and mitigating environmental liabilities. In addition, PG changes the model of waste handling from cost-oriented disposal to revenue-generating production of valuable products like energy, chemicals, and construction materials.

7.2Challenges (A Deep and Critical Dive)

Plasma gasification is challenged by high capital costs since the cost per tonne of capacity is high and expansion is limited by the scattered nature of waste, which renders transport to central points uneconomic. Investors tend to view the technology as risky because of its comparative newness and technological sophistication relative to traditional incineration, with the consequence of financing being more expensive and challenging to obtain. Operationally, the high temperatures within the reactor reduce refractory life, resulting in expensive and time-consuming shutdowns for maintenance. Furthermore, fluctuations in waste feedstock composition, calorific value, and moisture interfere with thermal balance, which is resolved by highly advanced pre-processing equipment like mechanical-biological treatment and advanced controls, incurring additional capital and operational costs. Syngas cleanup is probably the most urgent challenge, in which achieving high purity levels for power production or chemical synthesis requires extremely sophisticated gas treatment trains, which can easily capture up to half of the entire plant investment.

8. Future Research and Development Directions

*Materials Science:Extensive R&D must be carried out to create next-generation refractory materials that have longer service life and greater resistance to corrosion from slag and thermal shock. Analogously, stronger and more efficient electrode materials for plasma torches would drastically lower OPEX.

* Process Intensification and Catalysis: In-situ catalysts (thrown into the gasifier or in the plasma zone) research may reduce the operational temperature needed for full gasification, and in turn decrease the huge energy input to the plasma torches and enhance the net energy balance.

* Hybridization and System Integration:Optimization of total efficiency can be achieved through the development of hybrid systems. For instance, integration of PG with an AD plant located in the upstream: the AD treats the wet organic fraction and provides biogas and digestate, while the PG unit treats the digestate and other dry high-calorific waste and generates heat and power for the AD process.

* Carbon Capture and Utilization (CCU): Combining PG with post-combustion capture from the syngas engine or turbine may produce a carbon-negative waste management process, producing carbon credits and adding to its climate change mitigation value.

* Advanced Process Control and AI: Advanced AI-based process control systems could streamline reactor performance in real-time, adjusting to changes in feedstock quality, with the maximum syngas yield and quality, and minimum energy usage.

9. Policy and Market Innovation

Technology is not enough. Mass adoption calls for facilitation frameworks:

* Valuing Environmental Value:Governments have to adopt policies that economically value PG's environmental values, like advanced disposal fees for landfills and incinerators, carbon pricing, and "green" tipping fees.

* Standardized Off-take Agreements: Establishing standard power purchase agreements (PPAs) for waste electricity that account for its dispatchable and renewable nature, and assured offtake contracts for renewable syngas.

* Investor Risk Reduction: Government loan guarantees and public-private partnerships (PPPs) can reduce the perceived technology risk and attract the necessary large-scale investment.

10. Conclusion

According to the evidence, it is apparent that Plasma Gasification (PG) is still not an economically competitive energy technology in most markets. Its value proposition at present largely stems from its superior environmental performance compared with conventional waste-to-energy or landfill disposal, but not from cost parity. This is because PG systems often involve high capital investment, complex plasma torch operation, and energy-intensive processes that limit commercial scalability. As a result, its most likely initial commercial deployment may not be bulk Municipal Solid Waste

(MSW) treatment but destroying specifically individual, high-hazard waste streams (medical, industrial, chemical, pharmaceutical, PFAS-tainted), where other treatment options are prohibitively expensive or where rigorous regulatory systems mandate destruction efficiencies above 99.9999%.

In the medium term, the techno-economic profile is to be further supported through advances in plasma torch efficiency, integration of high-performance syngas cleanup systems, modular reactor design, and hybridization with renewable energy sources (e.g., solar or wind). Besides, valorization of co-products such as construction-grade vitrified slag, high-value recovered metals, and platform chemicals based on syngas provides diversified revenue streams that are capable of bridging the economic gap increasingly. Increased process integration with combined heat and power (CHP) units or hydrogen recovery would also be more profitable and able to achieve the clean energy goals.

From a greenpoint, PG has near-zero dioxin and furan emissions, efficient sequestration of toxic elements in vitrified slag, and significant reduction in landfill reliance. Its capacity to treat heterogeneous and toxic wastes makes it a prime contender for future compliance with waste policy requirements, especially as governments strengthen prohibitions on incineration and focus on resource recovery in circular economy strategies. In addition, PG can contribute to climate action targets by replacing fossil-based fuels via syngas use and by diminishing methane emissions from landfilling.

Socio-economically, large-scale take-up of PG will demand enabling regulatory contexts, incentive investment and public-private partnerships to bear initial expenses. Demonstration projects and regional-scale deployment are needed to generate confidence in its operational reliability and economic viability. Joint ventures with industries that generate hazardous by-products have the potential to create niche but stable markets, while integration into urban waste management systems may develop after economies of scale have been realized.

Lastly, PG's role in sustainable waste management is poised to transform under policy agendas that discourage landfilling, limit traditional incineration, and encourage green technology. In such a scenario, plasma gasification can progressively move from being a niche technology for specialty wastes to a platform technology applicable generally, which addresses environmental protection, renewable energy, and resource recovery at the same time, complementing its role in promoting circular economy approaches.

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