Small Scale Plasma Gasification of Municipal Solid Waste

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Abstract- *The goal of this project was to develop a prototype plasma gasification system to treat municipal solid waste (MSW) with minimal regulated emissions in a footprint small enough to be transported for a wide range of applicability. This project started with a review of current MSW treatment methods and of the emissions produced from thermal breakdown of MSW. A review of air quality regulations and emission control technologies was then used to select the emission control systems to be used for a small-scale plasma gasification system.*

This plasma gasification system began with a plasma torch and cooling system being designed, built, and tested with various electrode materials and designs. The torch was tested using compressed air, nitrogen, and a mixture of argon and hydrogen. Tungsten was chosen for the positive electrode and copper for the negative electrode, with compressed nitrogen as the process gas. A gasification chamber was designed and built to handle the molten material and act as a platform for the torch-centering device, exhaust port, and viewing window. Several emission control systems were built based on expected pollutants of MSW decomposition.

These controls include a particle separator, catalytic converter and a packed column scrubber. Gas and atmospheric sensors were then programmed and installed in the exhaust gas stream.

This prototype plasma gasification system was built with the intent of testing various materials one at a time and measuring the emissions produced. This data would then have been used to modify and improve the emission controls used to eliminate or capture any contaminants in the syngas, with the intent of having the syngas be a mixture of only hydrogen and carbon monoxide. Later additions would include a fuel cell to be used with the hydrogen, a heat exchanger and turbine to recover energy from the heat produced, and material recovery systems for the contaminants detected.

Keywords- Plasma Gasification, Municipal Solid Waste, Tamil Nadu, Waste-to-Energy, Sustainable Waste Management, Syngas, Decentralized Solutions

I. INTRODUCTION

Municipal Solid Waste (MSW) management is one of the most pressing environmental challenges facing Tamil Nadu today. With rapid urbanization, industrialization, and population growth, the quantum of solid waste generated across the state has increased significantly. As per the Tamil Nadu Pollution Control Board (TNPCB) and the Ministry of Housing and Urban Affairs (MoHUA), Tamil Nadu generates approximately 14,600 tonnes of solid waste per day, with major cities like Chennai alone contributing over 5,400 tonnes per day. The composition of this waste includes biodegradable, recyclable, and a significant fraction of non-recyclable and hazardous materials.

Despite various initiatives under the Swachh Bharat Mission and Solid Waste Management Rules 2016, most of the collected waste still ends up in landfills or open dumps, leading to severe environmental degradation, groundwater contamination, and emission of greenhouse gases like methane. Moreover, land scarcity in urban and semi-urban areas has rendered large-scale landfill-based waste management models unsustainable in the long term.

In this context, plasma gasification emerges as an innovative and viable solution, especially in small-scale and decentralized formats suitable for Tamil Nadu's urban and peri-urban municipalities. Plasma gasification is a high-temperature thermal process that uses electrically generated plasma arcs to convert organic and inorganic waste into syngas (a mixture of hydrogen and carbon monoxide) and a vitrified, non-leachable slag. Unlike incineration, it ensures minimal toxic emissions, and its byproducts have potential value in energy generation and construction industries.

Adopting small-scale plasma gasification systems tailored to Tamil Nadu's diverse waste profiles and space constraints can transform the waste management landscape. These systems not only offer zero-landfill potential but also enable local bodies to harness waste-to-energy benefits in a cleaner and more sustainable manner. With strategic implementation and public-private partnerships, small-scale plasma gasification could support Tamil Nadu's goal of becoming a model state in circular economy practices and green energy transitions.

II. LITERATURE REVIEW

Municipal Solid Waste (MSW) management has become a critical environmental issue worldwide due to rapid urbanization, industrialization, and population growth. Traditional waste disposal methods such as landfilling and incineration have resulted in several environmental challenges, including groundwater contamination, methane emissions, and the release of toxic gases. Tamil Nadu, like many Indian states, faces increasing MSW volumes, averaging 14,000–15,000 tonnes per day, with limited landfill space and inefficient segregation practices [TNPCB Report, 2023]. There is a pressing need for sustainable, clean, and decentralized waste treatment methods. Plasma gasification is an advanced thermal treatment process that uses a plasma arc (temperatures > 3,000°C) to convert organic waste into syngas ($CO + H_2$) and inorganic waste into inert vitrified slag.

Unlike incineration, it operates in a near-oxygen-free environment, drastically reducing harmful emissions such as dioxins and furans. Research by Gomez et al. (2009) highlights plasma gasification as a zero-waste technology with the dual benefits of energy recovery and minimal environmental footprint. The syngas produced can be used for electricity generation, while the vitrified slag can serve as a construction material.Countries such as Japan, South Korea, and Canada have demonstrated successful applications of plasma gasification in waste-to-energy (WTE) systems. For example, the Hitachi Metals plant in Japan processes 300 TPD of MSW, converting it into electricity with minimal emissions [Tanigaki et al., 2012]. The Uta shinai plant in Japan and Ottawa's Pasco Energy Group also implemented pilot projects, although challenges in operational economics and feedstock variability led to mixed long-term outcomes. India has seen limited deployment of plasma gasification. The first plasma pilot plant in Pune, developed by BARC in collaboration with M/s. M. N. Dastur & Co., treated biomedical and hazardous waste. However, the lack of scalability, high initial costs, and policy hurdles restricted its expansion [MNRE, 2022]. Despite this, there is growing interest from both public and private sectors due to the urgent need to reduce landfill dependency and generate clean energy. The Swachh Bharat Mission and Smart Cities Mission have included decentralized waste-to-energy solutions as part of their long-term goals.

III. METHODOLOGY

Dumps

The simplest, cheapest method of waste disposal is an open dump, which involves piling waste on the ground near the source. Open dumps are sometimes burned to reduce volume and often catch fire as combustibles decompose, producing smoke along with methane gas upon decomposition of organic waste. These dumps are commonly not bottom sealed from chemicals of decomposition leeching into the surrounding water bodies, which are usually close to the communities that fill the dump. Open dumps allow release of the chemicals and decomposition byproducts into the environment. These chemicals often cause health and safety issues for the nearby communities. Higher income countries typically prohibit open dumps. There are many lower income regions of the world where open dumps still exist.

Landfills

Engineered landfills, a more sophisticated type of dump, are typically designed with a bottom lining system and covered or topped every day to minimize pollution released. In European and American landfills, the ground is typically covered with an impermeable or semi-impermeable geomembrane followed by a geotextile and a system of leachate collection pipes laid on top of the geotextile. The leachate collection pipes are then covered in a mineral barrier and finally a drainage layer to allow leachates to reach the pipes. The waste is then laid on top of this lining system. The cover is typically made up of the same type of liner placed on top of the waste, with additional soil on top of the cover. Gas collection pipes are installed to capture the gases produced within the landfill. These gases are collected for use as fuels and typically are composed of 45-55% methane and 40-50% carbon dioxide. Some landfills choose to burn the methane with flares and release methane combustion products directly into the environment.

Landfills do occasionally catch fire during gas extraction or from sparking of equipment. Aerobic microbial reactions can also increase the temperature and ignite gases within the landfill.

Landfill coverings are meant to seal in the gases produced by decomposition of organic matter and prevent rainwater from entering. Landfill linings are designed to prevent liquids draining from the waste to reach the soil or the groundwater; however, the linings are only designed to last so many years. The linings can fail through erosion, freeze-thaw cycling, wet- dry cycling or subsidence of the soil below at some point, which will allow leachate to be released.

The majority of leachates from landfills are released from precipitation infiltrating the landfill and leaking through the liner. One study found that 42.76% of the total precipitation leaked through the Ano Liosia landfill of the Attica region of Greece[12]. The leachate from this study found high levels of ammonia (NH_3), phosphate ions (PO_4^{3-}), sulfate ions (SO_4^{2-}), chloride ions (Cl^-), potassium ions (K^+), along with iron and lead ions in the groundwater close to the landfill. This study did not test for hazardous industrial chemicals, as there is not much industry in that area of Greece.

The landfill studied in Greece also had high chemical oxygen demand (COD) and a relatively low biological oxygen demand (BOD), with a relatively low ratio of BOD/COD. This low BOD/COD ratio suggests that the organic matter in the landfill is not easily biodegradable. In 1991, an archaeologist, Dr. William Rathje at the University of Arizona, worked on

"The Garbage Project" to determine the archaeology of contemporary landfills and found "such preserved perishables as heads of lettuce, Kaiser rolls, hot dogs, corncobs with their kernels intact, guacamole, and literally tons of datable, readable newspapers". If guacamole can be found after years in a landfill without major decomposition, then that organic matter in landfills is not doing what organic matter is supposed to with the design of current landfills. Dr. Rathje's study analyzed landfills in Arizona, which does not receive as much precipitation as in many other parts of the world where leachate would be a greater issue.

Incineration

Incinerators for MSW were first built in the US in 1885 as the first level of technology above landfills. This process involves continuously feeding the waste into an incinerator with waste serving as the fuel source. The trash is burned in a chamber with air continuously injected, allowing for combustion and the high temperature chemical reactions that can form polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) and other pollutants. The emissions from MSW incineration often include carbon dioxide, methane, nitrogen oxides, PCDDs, PCDFs, particulate matter including heavy metals, volatile organic compounds (VOCs), and any byproducts formed from the multitude of materials that make up MSW. These systems commonly use air as the source of oxygen for combustion so there is little control over the reactions that form many of the emissions produced during combustion. The byproducts of this process include substantial atmospheric pollution and ash. The ash produced is commonly composed of bottom ash and fly ash, where fly ash includes the fine particles that remain airborne. As MSW can contain anything people throw in the trash, there is a wide range of chemical compounds that can form, which requires extensive emissions controls at each plant. When the Clean Air Act came into effect in 1970, the existing MSW incineration facilities had to either install emission control technology or shut down. In the 1990s, the Maximum Achievable Control Technology (MACT) regulations set forth by the EPA recognized the dangers of PCDDs and mercury emissions, resulting in another round of retrofitting emission controls or shutting incineration plants down.

Pyrolysis

One solution to reducing the emissions from incineration is to reduce the concentration of oxygen in the combustion chamber. An oxygen starved high temperature process is called pyrolysis. The byproducts of pyrolysis include a low sulfur liquid similar to fuel oil, char, a fraction of water, and gaseous emissions. This process has reduced gaseous emissions as compared to traditional incineration due to the lack of air in the heated chamber. The gaseous emissions from atmospheric pressure pyrolysis include carbon monoxide, carbon dioxide, hydrogen, C_1 to C_7 hydrocarbons and small amounts of water vapor and methyl chloride. The composition of the byproducts is approximately 40 wt.% oil, 35 wt.% char, 10% gases and 15% water. The oil produced from pyrolysis is typically used as fuel oil for energy production as the oils are composed of many sizes of molecules and depend highly on the MSW feed material. A comparison of pyrolysis versus incineration of certain materials found that the production of PCDDs and PCDFs is greatly reduced, yet still not eliminated with pyrolysis.

For example, with polyvinyl chloride, the combusted concentration of PCDD/PCDF was 4500 pg I-TEQ/g* while the pyrolysis concentration was 215 pg I-TEQ/g. A similar effect was seen with a sewage sludge containing a high concentration of metals which produced 1700 pg I- TEQ/g PCDD/PCDF concentration when combusted versus 232 pg I-TEQ/g PCDD/PCDF

* pico-grams PCDD/PCDF expressed as International Toxic Equivalents/gram waste material

concentration through pyrolysis. The other materials studied had far lower production of PCDD/PCDFs and had similar results with a lesser percent difference. Pyrolysis does reduce the production of PCDD/PCDFs, decreasing the required emissions controls; however, the process does still produce unwanted byproducts.

Pyrolysis is used more often to process bio-mass than solid waste to increase the quality of the oil produced and allow for a lower temperature chamber to be maintained. This process is only feasible for specific homogeneous feed materials, as it must be done at specific controlled temperatures depending on the feedstock. This could be a suitable process for organic material that is not easily composted or as a method for bio-fuel production. The solid residues produced must still be sent to a landfill, so it is not a full treatment for waste materials.

Plasma Gasification

Plasma gasification is the process transmitting a high electric current through a stream of flowing gas, resulting in the stripping of electrons from the passing molecules to create a high temperature field of ionized gas. When applied to waste materials, this high temperature field breaks chemical bonds and is full of radicals, electrons, ions and excited molecules that can reach temperatures in the range of many thousands of degrees Kelvin, with some reaching 10,000 K. At these temperatures, the inorganic material is decomposed into vitrified slag and the organic material fully decomposed into gaseous state. This process occurs in a highly insulated chamber of refractory material, where the slag can form a pool and be released in a controlled manner and the gases generated can leave through an exhaust port to refining processes. The exhaust gases are mainly hydrogen and carbon monoxide, with low levels of contaminants that need to be removed. This refined mixture of hydrogen and carbon monoxide can be used for fuel purposes and is often called syngas (synthesis gas).

There are several benefits of plasma gasification over combustion processes. When plasma is used as the energy source for waste decomposition, less oxygen is required to process the feedstock. This reduction in oxygen requirements allows plasma gasification to have reduced formation of SO_2, NO_x and PCDD/PCDFs. The volume of process gas is also lower due to reduced oxygen demand for combustion; consequently, the equipment for cleaning the exhaust gases can be smaller and less expensive. The energy density of plasma is also much higher than the feed materials used in combustion processes, which can reduce the size of the destruction chamber. With the high energy density, plasma gasification is able to crack tars and chars that are a byproduct of pyrolysis. The high energy density means that any particulates or residues produced within the cleaning process can be sent back to the input to be processed.

Plasma gasification systems have smaller footprints than landfills and do not produce the associated odors of decay. This gives plasma gasification plants more locational freedom and can be spaced out to minimize waste transportation distances. Small-scale, decentralized plasma gasification systems would reduce the emissions from waste collection and allow material and energy recovery from MSW. Decentralized systems built with sorting, recycling and composting facilities placed at the source of MSW would greatly reduce the travel time for waste collection vehicles by reducing the travel time to and from their collection routes. This would also require far less real estate than landfills currently need and prevent the environmental damage commonly associated with landfills. Small modular plasma gasification systems could be stationed at landfills to mine and treat the materials buried to prevent future environmental damage, reduce the footprint of the landfill or even extend the lifetime of operation of waste management systems. Smaller scale waste treatment systems also have the benefit of reduced capital costs, which is a major hindrance to new waste treatment technologies.

This project considers treating MSW using plasma gasification on a small scale to reduce the capital cost and the carbon footprint of large-scale waste management facilities. The goal of studying plasma gasification is to eventually eliminate the need for landfills and to excavate existing landfills to restore them to their natural clean state while reclaiming or mining the landfilled materials. If the capital cost and operating costs can be sufficiently reduced, then this technology could be used even in the lower income regions of the world to dispose of the waste being sent to open dumps and landfills. In application, this process could be delivered to parts of the world with no effective waste management system.

IV. RESULTS

The goal of this project was to develop a prototype plasma gasification system to treat municipal solid waste (MSW) with a design aimed at minimizing regulated emissions in a footprint small enough to be transported allowing waste management directly at the source. A small-scale plasma gasification system was designed and built with emission controls in place. The built system is contained in a package small enough to fit on the back of a standard pickup truck. Overall, this project met its goals of a working small scale plasma gasification system with emissions controls that can be transported. However, the gas cylinders required to produce plasma would also need transport and the built system requires both a 220v circuit and a 110v circuit to work. While the built system has been tested, the emission controls incorporated in this pilot-scale design will benefit from additional research.

The plasma torch built for this prototype did not produce a plasma plume large enough to fully break down the materials added to the chamber. Part of the failure is due to a lack of sufficient power to the torch. With more power than that of a 220v, 20-amp circuit available in the PSU lab, the torch would be able to increase the degree of ionization of the passing carrier gas. This is a prototype plasma gasification system, though the plasma torch and gasification chamber were not matched in capacity. This torch may be improved with many more hours of testing and nozzle designs, which was not the main focus of the project.

This project currently has several consumables and power requirements that would limit its application in many parts of the world. The compressed gas that the torch runs on must be reasonably pure nitrogen, a mixture of argon and helium, or carbon dioxide. These compressed gases are not available in many of the places of the world that do not have waste management systems. The plasma torch design for this project was meant to run on compressed air, which may have been ambitious.

With minimal electrical engineering and plasma torch background, there were many challenges with this project. The plasma torch is far from optimal, yet is still a far cheaper option than commercially available plasma torches that are built for similar purposes. Much of the testing required in the project was getting the torch to work enough to continue with other aspects of the project. After researching more about plasma torches that are used in industry, the problems of electrodes and process gases could be greatly simplified by using steam instead.

The 110 volt and 220volt power requirements would also prevent this system from being usable in many parts of the world, unless there was some power generation and storage built into the package for startup, such as wind turbines or solar cells along with a battery pack. The scrubber system also has chemical requirements to keep the pH high enough to clean the exhaust that may be unavailable in other parts of the world.

The emission control components used are not expected to efficiently treat or capture CO or CO_2. With a varying fuel to air ratio, the catalytic converter will not be optimally oxidizing CO and will likely let much of this CO pass by unoxidized. The scrubber is not expected to absorb much of this CO_2, as there does not seem to be a long enough residence time in the scrubber for the volume of exhaust gases produced. The solubility of these gases in water also decreases with increasing temperature, further reducing the capacity for absorption into the scrubber liquid.

Without a heat exchanger in place before the scrubber, the exhaust gases to be treated will likely increase the temperature of the scrubber liquid by a fair amount. The effectiveness of the scrubber still needs to be tested to verify whether it can handle treating the volume of exhaust gas produced. It is expected that the scrubber and scrubber reservoir size should be increased to meet the treatment requirements based on the flow volume of exhaust gases.

As the scrubber in this system removes pollutants from the exhaust gas, it will build up these compounds in the scrubber reservoir. Removal of these compounds has not been included in this project, and is an important part of treatment. These compounds can be separated through further processing. Removal and recovery of materials from the exhaust gases are necessary to make the plasma gasification process desirable compared to pyrolysis or incineration waste reduction processes.

The way municipal solid waste is currently dealt with is not sustainable. Much of the MSW is buried to slowly decay and release pollutants that must be remediated for years to come. The processes used today to reduce the volume of this waste and generate power still cause environmental issues that need to be considered. Plasma gasification is a promising solution that still needs optimization, yet is able to greatly reduce the volume of waste that is produced while providing the opportunity for material recovery and energy generation. With recycling, composting and re-use of materials, plasma gasification can be used to account for all the other materials that have reached the end of their useful life. With the addition of gas separation, fuel cells for energy production from the hydrogen gas, a heat recovery system, and material recovery systems applied to the syngas, this technology has the potential to change the way society deals with waste. Plasma gasification of MSW only needs people to focus their time and resources to optimize the technology and focus on the future of how waste is treated. This technology can help the economy go from a cradle to grave perspective to a cradle to cradle perspective.

Small-scale systems like the one built for this project could be built all around the world to treat waste where it is produced to reintroduce raw materials back into the economy. The more small systems that are built, the shorter waste collection vehicles need to travel and fewer emissions will be produced. Small-scale systems also have a far lower capital cost than the metropolitan sized processing plants, which would allow them to be built in a shorter period of time. When plasma gasification systems are built on mobile platforms, the plasma systems could be used for disaster cleanup or to help those parts of the world with no waste management systems in place to reduce their pollution.

VII. CONCLUSION

Small-scale plasma gasification offers a promising, eco-friendly, and scalable solution for Tamil Nadu's municipal waste problem. It not only addresses waste disposal but also generates clean energy and reusable byproducts. With proper planning and support, this technology can be integrated into Tamil Nadu's urban infrastructure, especially in towns and peri-urban areas.

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