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RESEARCH ARTICLE

Hydrogen as Potential Primary Energy Fuel for Municipal Solid Waste Incineration for a Sustainable Waste Management

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ABSTRACT Municipal Solid Waste (MSW) management has always been a challenge for the community impacting environmental sustainability. The anticipated reasons include an increase in population and prosperity. Among all the viable methods for MSW management, incineration technology is the most matured and feasible method. Incineration technology is based on combustion process of waste assisted by fossil fuels. These fuels are not only depleting with every day, but also a source environmental hazards upon burning. Current study investigates the feasibility of hydrogen as a primary combustion fuel for municipal solid waste (MSW) incineration. A vertical shaft type incinerator has been designed with the ability to operate on pure hydrogen. A pre-mixed hydrogen and oxygen fuel in the stoichiometric ratio has been fed through specially designed burners. The burners have been so designed to achieve homogenous heat distribution. To determine the working of incinerator at maximum allowable moisture content, a variety of homogeneous and heterogeneous MSWs with high moisture percentages between 60 and 90% have been tested. The maximum temperature of the incineration has been recorded to be 850°C. A high reduction in weight percent i.e., 86-94%, and loss on ignition (1.74%-6.41%) have been observed. The hydrogen-based incinerator exhibited the highest performance for homogenous paper and food waste (1kg) with 60% and 87% moisture content respectively. The energy consumption was 108Wh and 321Wh respectively and achieved 97.14% and 88.88% reduction in weight respectively. Increase in moisture content of the waste leads to decrease the performance of hydrogen based incineration system.

INDEX TERMS Municipal waste management (MSW), hydrogen, incineration, fuel.

I. INTRODUCTION

One of the most critical things in municipalities and the businesses they are linked with is managing solid waste. It comprises the collection, transportation, and disposal procedures [1]. Around 2.01 billion tons of municipal solid waste has been generated annually and is expected to increase to 3.4 billion tons by 2050 [2]. The main reasons are an increase in population and prosperity. East Asia and the Pacific region contribute to 23% followed by Europe and the South Asian region (20% and 17% respectively). MSW comprises of majority of household waste. This waste has significant fraction of food waste, wood, paper, and sometimes materials derived from fossil fuel like plastics, rubber and fabrics. Waste composition in low-income countries have more organic or food waste than high-income countries [3]. Effective municipal solid waste management is acknowledged as the most demanding method for preserving the

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environment and fostering economic growth [4]. Energy can one of the productive output while treating this MSW. Waste to energy has become a vibrant industry of approximately worth USD 37.6 million in 2020 which is expected to raise about USD 44 million by 2024 [3]. By 2015, 1179 incinerators were built globally with a capacity of 700000 MT/d out of which 80 WtE incinerators plants working in the USA alone that were generating 2769 MWh electricity for the grid by processing 96000 tons of MSW per day [3]. Till now China has the largest capacity of incineration MSW with more than 240000 MT/d. Alone in China, WtE incineration plants have grown rapidly from 3.70 to 133.08 million metric tons of designed capacity between 2003 and 2018, respectively. This has increased the percentage for incineration in China that was 14.66% in 2010 to 44.67% in 2018. A typical WtE plant in China with a capacity of 1000 t/d and a life expectancy of 25 years, expects relevant margins and stable profit with a payback period of 11.3 years [5]. In 2012, a projection was made by the world bank that WtE will have the potential to provide 11 Exajoules of energy globally by 2050 [3]. Despite WtE available potential and different incentives, still, 75% of the global MSW is landfilled. Different European countries like Sweden, Denmark, Finland, and Estonia are global leaders in this industry by incinerating at least 50% of municipal solid waste which result reduce their landfill to 10%.

Different waste management techniques, such as thermal, biological conversion, or landfilling, not only address issues related with municipal waste [6] but can also be a potential source for energy generation [7]. These technologies depend upon the composition and characteristics of the waste that is available. Unfortunately, 50% of the waste that is collected is improperly managed. Instead, it is openly burned or dumped in landfills which contributes to more than 3% of global greenhouse gas (GHG) emissions [8, 9]. Only methane (produced by the decomposition of MSW in the open air) accounts for 1-2% of GHG emissions [10].

For waste management, several thermal processes are employed with a view to reducing GHG emissions. Thermal processes like plasma are typically employed to safely dispose of medical waste. It is seen to be more environmentally friendly while transforming organic-based waste [11]. In this process, an extremely high temperature is created of approximately 5000 – 14000 °C for creating plasma using various gases (N2, Ar, H2) for treating waste [12]. Although Plasma incineration is a clean technology it involves additional costs and technical expertise that were not assigned to other waste management technologies [13]. That is due to expensive plasma sources (plasma torch or arc), high level of automation, the specific refractory lining of the chamber, and its operative technology. Only a plasma source assembly alone can cost more than $50000 [14]. An average plasma incineration plant can cost USD 65 – 200 million with a capacity of treating 500 tons MSW/day [12]. There are two plasma waste incineration plants named Plasco in Canada and Euro-Plasma in the USA that have a total cost of 149 USD/ton [15]. Operation cost is also a challenge for this plasma technique. Specifically, due to the expensive high power DC supply required to power up plasma source. This makes plasma a major liable chunk of energy-intensive processing industries that are responsible for 30% of GHG emissions [16]. Parameters like the shape of the incinerator, fuel inlet, and airflow affect the incineration process. Even research on using microwave technology to handle waste in an eco-friendly manner has been ongoing for a long time. Although the cost of the capital cost of microwaving is the same as that of an effective and efficient incineration technology it cannot work at a large scale and also it's not a co-generation process like incinerators [17]. Also due to the working principle of microwave technology it is not suitable for all types of waste as dielectric properties of the treated waste streams are not homogenous [18]. Normally microwave technology is used to vitrified bottom ash of incinerated waste. But it required approximately 3300kJ/kg of high energy [19].

Among all the commercially available thermal processes incineration is most widely used as a thermal conversion technology for municipal solid waste [20]. This is due to its ease in operation, lower cost, and ability to process a wide variety of feed [21]. The global market size of incinerators reached 14.35 billion USD in 2021 and is expected to surpass 18.87 billion USD by 2027 [22]. Landfilling is not always a viable solution for waste management. As in UAE landfilling is not an option due to hydrological reasons. Hence selection of waste management technology is selected on the advantages and disadvantages (summarized in appendix table 1s [23]) of the technologies that complements the scenario of a specific region.

Incineration plants has potential to address both concerns of waste treatment and energy generation from waste. This technology has a potential of 100MW of electricity [24] and help in reducing carbon emissions. In Hyderabad one of the cities of Pakistan, there is a maximum potential available in biochemical and thermo-chemical methods for power generation [25]. Moreover, incineration generates less GHG emissions compared to landfills. Incineration of the waste in the UK has a lesser impact on the environment than landfill and could easily meet up to 2.3% of the UK's total electricity demand which eventually saves almost 2 to 2.6 million tons of GHG emission [26]. Different European countries such as Sweden, Denmark, Finland, and Estonia are global leaders, incinerating at least 50% of MSW which in turn reduce their landfill to 10%. Landfilling results in 34.8% in reduction of waste with a rate of 87.8% stabilization while emitting a significant amount of 116.7 to 192.2 Kg-CO2Eq/t of greenhouse gases. Incineration is advantageous compared to landfills with a reduced rate of 79.2% and a 100% stable rate with controlled emission (124.3 Kg-CO2Eq/t). It is also advantageous for recovering 1163.1 MJ/t of electricity at the same time [23]. Incineration of MSW is extensively done in the western part of Europe from 35% to 80% of the waste produced [27]. The United States uses incineration to recover energy from 40% of the total solid waste generated.

In principle, an incinerator is a furnace that takes MSW as feed and uses fuel to burn it. Oxygen in the form of air has been provided through blowers to achieve near-complete and clean burning. Various design modifications and fuel types have been tried to improve the efficiency of the incineration process. There are different types of the incinerator that are being tested based on their working design. In a recent study, a rocket-engine-based incinerator was designed by adopting design concepts of swirl flow and nozzle shape applied to a furnace of power plants and a rocket combustor [28]. From the study, it was found that the shape and location of flame can affect the temperature of the incinerator by the flow rate of fuel, deflection and incline angles of nozzles, and dimensional size of the chamber. The other two technologies are most commonly used i. grated fire incinerator (GFI) ii. Fluidized bed incinerator (FBI). In both technologies, coal is normally used as an auxiliary fuel for the low heating value of waste. GFI saves more global warming potential than the FBI due to its higher net power generation from the combustion of MSW itself [29] but still, both technologies are still a major source of GHG emissions due to the use of coal as fuel.

For an effective incineration it requires low moisture content in the waste. It is the most crucial parameter as it can increase the weight of the waste without increasing the net yield. It can affect the process negatively if the moisture content of the waste is not at the right level, thus result in low yield and make the overall system economically ineffective [30], [31]. Above 50% of moisture content in waste cannot auto-ignite and required auxiliary fuel for incineration [32]. Fossil fuels (oil and gas) are normally used as auxiliary fuels. The major challenge to a sustainable future for incinerator has been the requirement of burning fossil fuels. According to a study, the global average MSW generation was approximately 2017 MT/year in 2016 which is predicted to rise to 2586 MT/year in 2025 and subsequently 3399 MT/year by 2050 [33]. In 2019, global MSW was generated approximately 3.1 billion tones [34]. By using this study it can be calculated that approximately 129.30MJ energy will be required to incinerate waste by 2025 [35], [36] which will be mostly coming from fossil fuels. It will not only consume valuable and depleting fossil fuels but also be responsible for a large amount of GHG emissions. To address this issue, the electrification of thermal processes (i.e., incineration) has been conceptualized and emerging technologies such as plasma, microwave, and resistance heating have been widely investigated with promising results.

Therefore, extra thermal energy is required in terms of either by fuel or electrification is required to incinerate municipal solid waste. In current scenarios, incinerators are fuelled with fossil fuel or electricity in case of Plasma or microwave technology. In this study, hydrogen has been employed as a green alternative to thermal MSW management techniques to avoid fossil fuel consumption and GHG emissions. Recently, hydrogen has attracted huge attention as an alternative fuel in many combustion applications due to its clean-burning, ease in utilization, and transportation [37], [38]. Also potential of hydrogen as fuel for treating hospital waste was tested successfully [39]. Life cycle assessment of various methods of producing hydrogen shows that electrolysis method using renewable energy sources through wind or solar PV are most environmental friendly in terms of least carbon dioxide emissions [40]. It is considered to be environmentally friendly and believe to be zero-emission future green fuel as it contains only water vapour as combustion emission upon burning with oxygen unlike fossil fuels [41], [42]. So for this study, fossil fuel used as an auxiliary fuel for incineration is replaced by hydrogen to investigate its effectiveness in waste management. A systematic study has been conducted by providing a pre-mix mixture of hydrogen and oxygen in stoichiometric ratio to the combustion chamber as the primary fuel to incinerate MSW. Moreover, an attempt has been made to measure the amount of hydrogen required for simulated waste with high moisture content and random MSW from various restaurants.

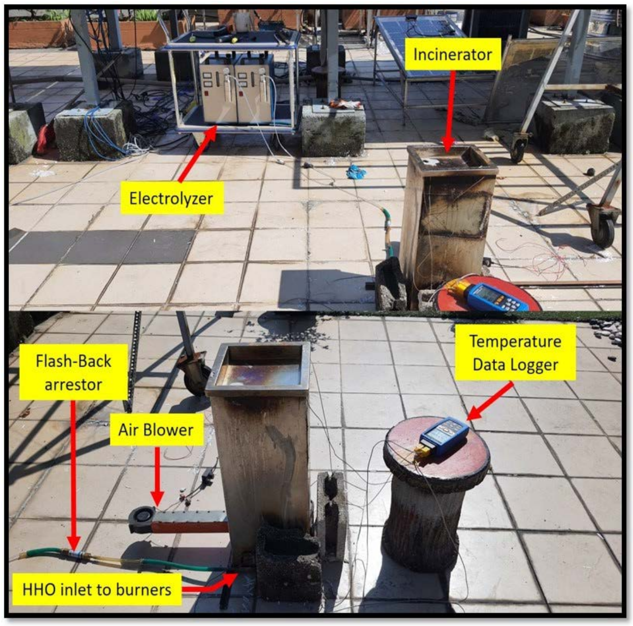

FIGURE 1. Complete setup to test incineration by using hydrogen as a fuel for the incinerator.

II. MATERIALS AND METHODS

Figure 1 shows the experimental setup consisting of Electrolyzer (model: H260, production capacity: 1.5 LPM (figure 1s, supplementary file), improvised Incinerator, data logger (model: TENMARS TM-747D), and thermocouples (K-type). The total flow rate from the two electrolyzers was hydrogen 3.5 LPM and oxygen was 1.5 LPM. A pre-mix mixture of hydrogen and oxygen in the stoichiometric ratio was provided to the combustion chamber. Temperature sensors were placed at specific locations and the temperature data was recorded using a data logger. For accurate monitoring of temperature changes in relation to operating time, a data recording step of 1 second has been set.

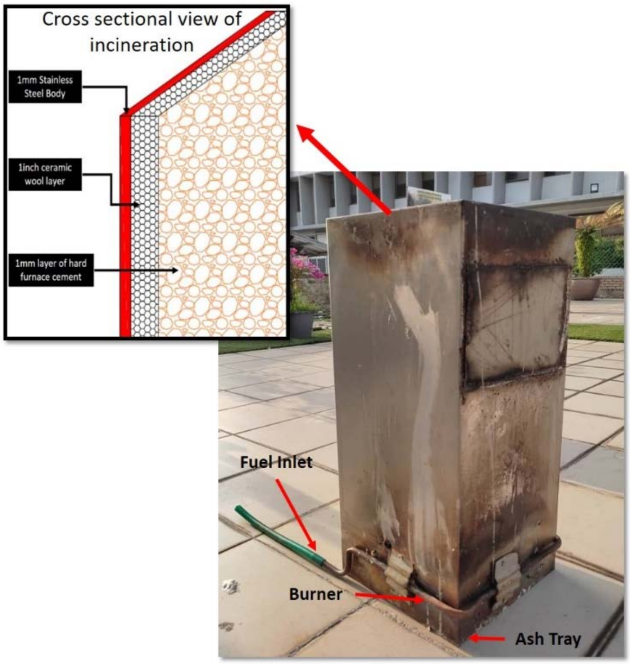

FIGURE 2. Fabricated incinerator for experiment along with its burners.

TABLE 1. Composition of waste collected for the experiment.

Batch Number	Type of waste	Amount of waste (gram)	Composition of waste
Waste 1	Food	1000	Eggshells, onion peels, potato peels, cabbage, spring beans, long beans
Waste 2	Paper	1000	N/A
Waste 3	Textile	1500	N/A
Waste 4	Mixed Waste Food = 500 Textile = 300 Paper = 300	1100	Eggshells, onion peels, potato peels, cabbage, spring beans, Watermelon rinds, paper, and cloth
Waste 5	Mixed Waste Food = 400 Textile = 300 Paper = 300	1000	Onion peels, eggs, Water Spanish, curry leaves, Methi leaves
Waste 6	Mixed Waste Food = 500 Paper = 500	1000	potato peels, eggshells, onion peels
Waste 7	Mixed Waste Food = 700 Paper = 300	1000	Onion peels, eggs, Water Spanish, curry leaves, Methi leaves, and paper

The incinerator is made of a stainless steel sheet with 1mm thickness with a dimension of 10inch × 6inch × 18inch. Further, this incinerator is layered with ceramic wool of 1inch thickness as shown in figure 2. Brick kiln cement was layered from inside to harden inside surface and to withstand high temperature. Therefore, after the complete assembling of the incinerator shown in figure 2 has active area available for the incineration process was 32 in^2 (8inch × 4inch) and volume 384 in^3 (8in × 4 in × 12 in).

A 10mm copper pipe was used for the burner wrapped around the incinerator at the bottom of the incinerator. These burners were fabricated by using a mini hand drill with micro tungsten carbide drill bits. Ash was collected using a detachable steel mesh at the bottom of the incinerator. This was used to remove the ash from the incinerator after the waste had been incinerated.

Current study is based on the scenario of Kuala Lumpur, Malaysia. Focus of this study was on the domestic kitchen (organic) waste as it is major contributor of municipal waste generation. Focusing the study scenario, figure 3 shows the random municipal waste being collected from restaurants and residential houses. Furthermore, the paper waste and textile waste have both been purposefully wetted to serve as simulated waste for comparison. Seven different trial runs of waste were made and their composition was noted. These wastes were further segregated and experimented with into two categories based on their nature (i) homogenous and (ii) heterogeneous. Based on the individual characteristics, paper, textile, and food waste were treated separately. This was done to examine the impact of hydrogen incineration on the various types of waste. For the heterogeneous nature of waste, all these basic types of domestic municipal household waste (paper, textile, food) were mixed in different ratios. This was done to have the characteristics of real-time waste from a simulated waste.

Before incineration combustion, both homogenous waste and heterogeneous waste were taken for testing moisture content. As high moisture content is a big issue for incineration. So water was added to the incinerator to test it with this new technique at high moisture content scenarios as reported in table 1. The composition of each waste is reported for each test batch.

Moisture content was estimated by having five different small samples of 50grams from each of the waste that was taken and chopped into smaller pieces. They are then weighted and noted by using a scale. These samples were then placed into an oven at 105°C for 24hrs. After 24hrs these samples were put in a desiccator to cool down so to avoid any absorption of ambient moisture. Then, again samples were weighed. This time it is the total dry weight of samples. So by using formula moisture content can be calculated for each waste sample.

$$\text{Moisture Content} = \left(\frac{\text{Wet Sample weight} - \text{Dry Sample Weight}}{\text{Wet Sample Weight}}\right) \text{X } 100. \tag{1}$$

All the five values of moisture content for each waste sample were then averaged to get accurate content.

The incineration residue has been tested for combustion efficiency. The residual weight was measured using a

FIGURE 3. Variety of Municipal waste used for incineration test (a) Textile waste; (b) Paper waste; (c) Food waste; (d), (e), (f), (g) Mix waste.

FIGURE 4. (a) Residue samples of seven different incinerated waste under test. (b) Sample heating in the oven for calculating moisture content of fly ash. (c) Sample heating in a muffle furnace for calculating loss on ignition of waste residue.

precision weighing balance (A&D HK-250AZ) and loss on ignition (LOI) has been measured according to ASTM D7348 standard. In brief, samples of the ash residue left of incinerated waste were collected in a crucible shown in figure 4a and weighted. In the first step samples in the crucible were heated at 110°C for 1 hour in a preheated oven (figure 4b). Then the sample was removed from the oven and left in a desiccator for 60mins to cool down before being reweighted. The weight loss observed in this step was the moisture content of fly ash. For the second time, this dried fly ash was then placed in a muffle furnace (Berkeley 'Thermolyne 30400 furnace muffle oven') and heated in a stepped schedule of 2 hours to attain 950°C (figure 4c) for 2hrs. The samples have been furnace cooled and weighted to calculate LOI.

III. RESULTS AND DISCUSSION

A. BURNERS SELECTION

The selection of burners was done on basis of rigorous experimental testing with different diameters of orifices. As different engineering factors are used to determine the compatibility of gases (fuel) with appliances. Wobbe index is the most common and simple to determine this compatibility [43]. As for hydrogen, the Wobbe index is around 48MJ/m3. This makes hydrogen gas compatible as it is within range of natural gas safety regulations for burners [44]. Although the wood index is within natural gas safety, burners used for natural gas cannot be directly used with hydrogen. This is because of combustion characteristics i.e., flame speed. The burner orifice size needs to be reduced compared to natural gas [43]. Therefore, dedicated burners were fabricated and were fed with premixed hydrogen and oxygen in a stoichiometric ratio.

The orifices of diameters i.e., 0.2mm, 0.3mm, 0.4mm, 0.5mm, 0.6mm, and 0.7mm have been tried keeping the mass flow constant at 0.8lpm (hydrogen and oxygen stoichiometric mixture). Figure 5 shows the flame lengths of visible flame and FLIR images from various orifice sizes. For orifice sizes 0.2mm and 0.3mm, no stable flame was observed. This is because of high gas velocities due to small orifice sizes which caused flame blow-off. A stable flame was achieved for 0.4mm burner orifice size for 0.8lpm gas flow. It was observed that the flame length increases with an increase in orifice size to a certain extent and decreases at higher orifice diameters. Further increase in orifice at constant flow

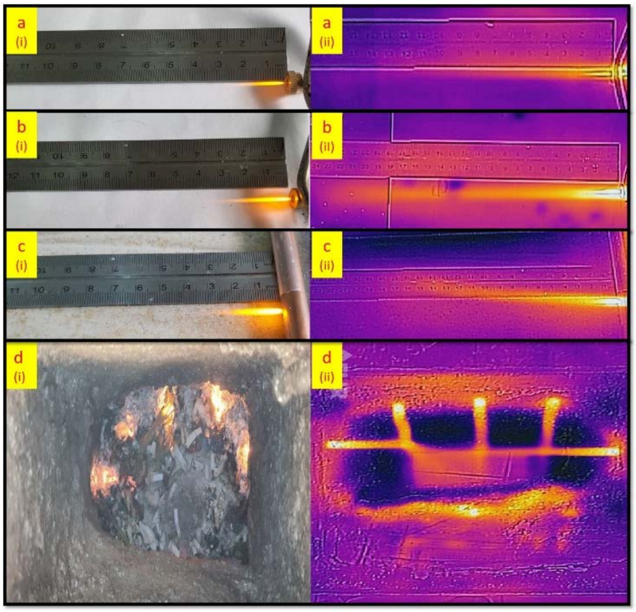

FIGURE 5. Testing of the flame length of the burner with the different orifices. Left side visible image, Right side FLIR image (a) Burner with an orifice of 0.4mm. (b) Burner with an orifice of 0.5mm. (c) Burner with an orifice of 0.6mm. (d) Inside view of the incinerator with burning flames.

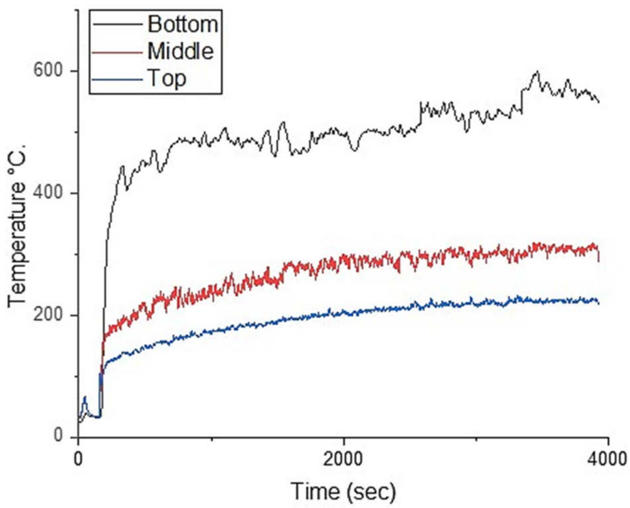

FIGURE 6. Temperature data at three different positions of empty incinerator using hydrogen as combustion fuel.

rate caused flashback and no stable flame was observed. Figure 5a (i & ii) shows a 2cm length of visible flame and ~8cm length of flame with FLIR imaging for 0.4mm orifice. Figure 5b(i&ii) shows 3.5cm length and ~23cm length for visible flame and FLIR imaging respectively for 0.5mm orifice. Further increase in orifice diameter to 0.6mm caused a decrease in flame length (3.5cm and ~14cm length of visible flame and FLIR imaging respectively) however, the flame intensified and burns with more noise and bright flame as shown in figure 5c (i & ii). Further increase in orifice diameter to 0.7mm resulted in flashback. Although visible and

TABLE 2. Data of the respective homogenous waste during incineration.

Batch Number	Moisture Content %	Energy Required (Wh)	Temperature °C	Time (Sec)	H2 given (liters)	Energy from H2 (Wh)	Energy from waste (Wh)	Percent energy provided by H2
Waste 1 (Food)	87	545.19	580	3200	107.2	321.6	312	58.99%
Waste 2 (Paper)	60	375.9	780	1100	36	108	1840	28.73%
Waste 3 (Textile)	90	845.9	800	2200	73.7	221	720	26.13%

*Additional 50% of moisture by weight is added using water in paper & textile used as waste

FLIR imaging for 0.5mm and 0.6mm orifice has the approximately same length, however burner with 0.6mm orifice diameter showed more effective flame (figure 5c(i) & d(i)). Based on the experiments and for homogenous heat distribution within the combustion chamber (chamber cross-section area: 6 × 6 inches), the orifice diameter of 0.6mm has been selected for our further experiments. The optimum number of orifices and diameter have been adjusted (figure 2s, supplementary file) for 3lpm fuel flow and cross-sectional area of the combustion chamber. Figure 5d (i & ii) shows the photographic and FLIR image of the adjusted number of burners respectively. Further increase in the number of burners leads to a reduction in flame length and possible flashbacks.

B. INCINERATION PROCESS

The incinerator was allowed to run on premixed hydrogen and oxygen in stoichiometric ratio for incineration. Figure 6 shows the relationship between temperature and time for the incineration chamber at various heights when run without garbage. The temperature close to the flame (the thermocouple was placed just 1-2 inches above the flames at the center) in empty condition reached approximately ~400°C in 200 seconds. The temperature reached ~600°C after 3500 seconds and maintained 600°C. In the middle section of the incinerator, the temperature was reached ~200°C in 500 seconds which was maintained at ~300°C after 2700 seconds of running the experiment. The temperature at the top of the incinerator reached ~150°C in 600 seconds and was maintained to ~200°C after 3500 seconds.

It has been observed that hydrogen as fuel can easily maintain a temperature of up to 600°C where the combustion of the waste is to be done. Overall keep the temperature of the incinerator good enough for an efficient incineration process for MSW. Note that the characteristic flame temperature of hydrogen is 2800°C.

The incineration experiments have been first conducted using individual waste i.e. paper waste, textile waste, and food waste. Figure 7(a) shows the time & temperature relationship for incineration and figure 7(b) shows schematic diagram of working of incinerator with MSW. The detailed parameters have been presented in table 2. The hydrogen supply has been

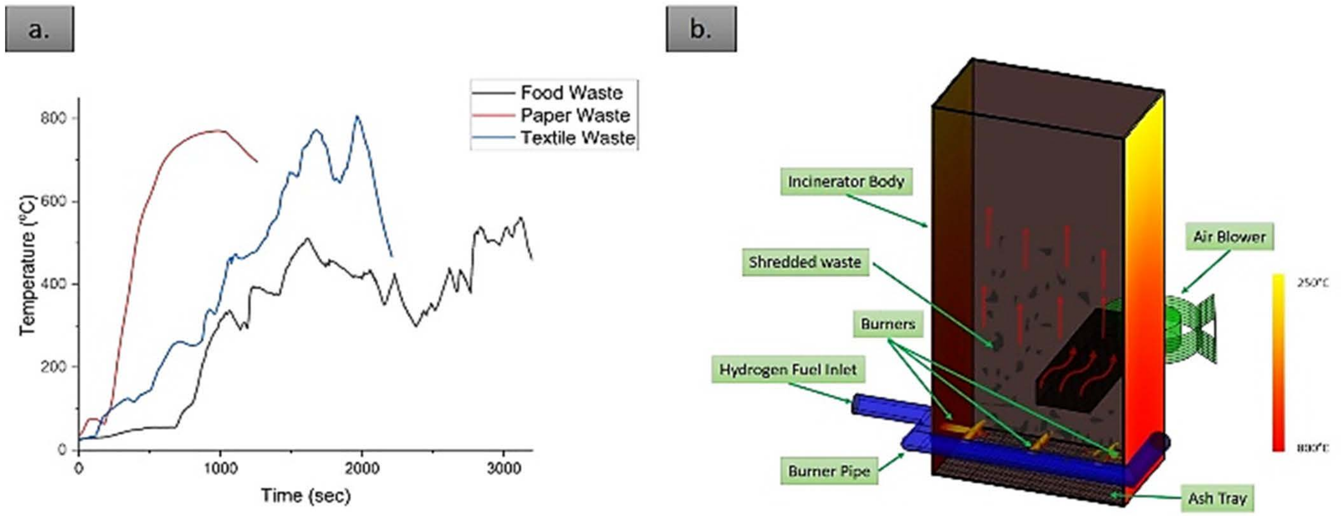

FIGURE 7. **(a) Temperature graphs for the homogenous respective wastes; (b) Inside working of incinerator.**

cut-off after reaching the temperature plateau and leaving the incinerator running (keeping the blower on) for complete combustion. As can be observed in figure 7a, the temperature for food waste of 1000g with 87% moisture content reached 580°C in 3200 seconds. The amount of hydrogen being consumed was calculated to be 107.2 liters which translates to 321.6 Wh of energy being supplied for the food waste. For the textile waste of 1.5 kg with a moisture content of 90%, the temperature reached ~800°C in 2200 seconds. Almost 73.7 liters of hydrogen equivalent to 221 Wh of energy was supplied for textile waste. In the case of paper waste, only 36 liters of hydrogen was required to raise 780°C of temperature in 1100 seconds for its complete incineration. Paper required much less time than others due to its highly combustible nature.

Further analysis on the energy required and energy from the waste was presented in table 2. As it was seen that calorific value of food waste, paper waste and textile waste is 8786 kJ/kg, 16600 kJ/kg, 17450 kJ/kg [45] which are equivalent to 2.4 kWh/kg, 4.61 kWh/kg and 4.84 kWh/kg respectively. Based on the calorific values and moisture content in waste in it was calculated that food waste can give 312 Wh, paper 1840 Wh and textile 720 Wh of energy.

In principle, the burners consumed hydrogen to burn and/or dry the highly moist MSW whereas, the blower provide the required oxygen for complete combustion of dried waste. The vertical shaft type design allows hot gasses to rise up and partially dry off the incoming feed as can be seen in figure 7b.

Compared to paper and textile trash, food waste processed at lower incineration temperature. This is because of the calorific value of paper and textile waste than food waste. Furthermore, the moisture content is a key factor affecting the time to rise in temperature. the initially provided energy was consumed to evaporate the water content. That was 545.19 Wh for food waste, 375.9 Wh for paper waste and 845.9 Wh for textile waste. The combustion of waste started after the removal of moisture content.

To test the hydrogen incinerator for real-time waste, different types of waste (food, textile, and paper) were mixed in a known ratio as presented in table 1. Figure 8 (a & b) shows the temperature vs time pattern and performance parameters (i.e., power consumed and time) respectively. Detailed parameters of the waste batches have been presented in table 3. The burning of waste with a higher moisture content has been found to take longer and use more energy. This is a result of the increased moisture contents, which demand more energy to evaporate that water. During the combustion, temperature rises as premixed hydrogen and oxygen are fed as fuel. Also, the waste itself acts as fuel as moisture content reduces due to high temperature. It has been observed that, as the waste incineration reached close to completion, the temperature starts to fall rapidly. This is because of no waste left for combustion in the incinerator chamber. It has been inferred that no more hydrogen fuel has been required from that time when the temperature falls significantly.

Waste batches 4, 5 and 7 have been incinerated in approximately 2100, 2000, and 2200 seconds respectively whereas waste 6 has been incinerated within 1200 seconds. Furthermore, it has been observed that the waste 6 rapidly reached ~800°C and maintain that peak temperature for a longer period, while other batches i.e., waste 4, waste 5, and waste 7 raised their temperature gradually and maintain peak temperature (i-e ~800°C) for a shorter period. This was happened due to the low moisture content in waste 6 compared to other wastes. Waste 4, waste 5, and waste 7 are required to dry-off high moisture content of the waste before waste could catch fire, while waste 6 has a low moisture content, therefore, the waste abruptly catches fire which in turn leads to a rapid rise in temperature. The amount of energy required for complete

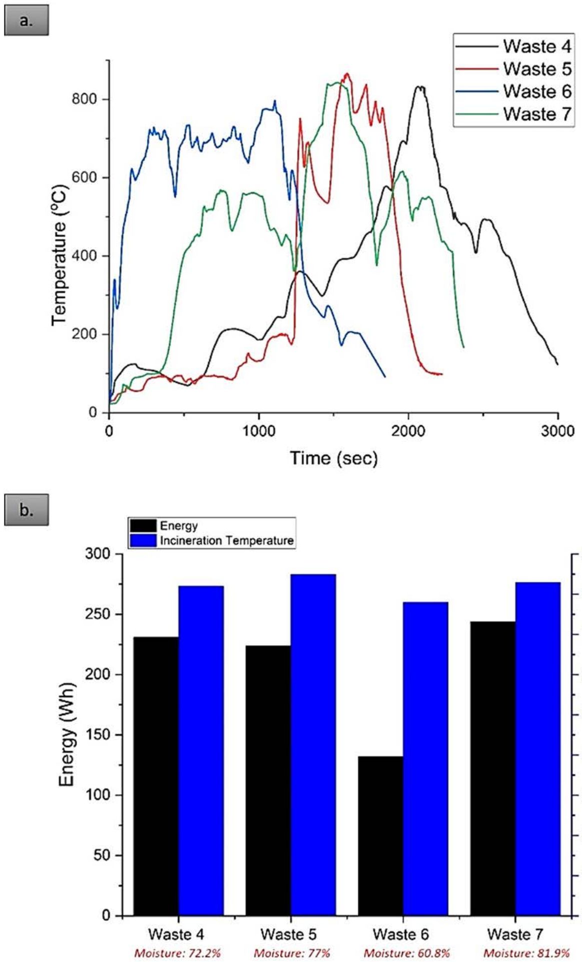

FIGURE 8. (a) Temperature graphs for the heterogeneous respective wastes (b) Energy required for incineration of respective waste.

TABLE 3. Data of the respective heterogeneous waste during incineration.

Batch Number	Moisture Content (%)	Energy Required (Wh)	Max Temp. (°C)	Time (seconds)	H2 given (liters)	Energy from H2 (Wh)	Energy from waste (Wh)	Percent energy provided by H2
Waste 4	72.2	497.69	820	2100	70	210	1082.5	42.20%
Waste 5	77	482.52	850	2000	68	204	869.4	42.28%
Waste 6	60.8	381.00	780	1200	40	120	1372	31.5%
Waste 7	81.9	513.23	830	2200	74	222	553.86	43.30%

combustion of each type of waste along with the maximum temperature reached has been presented in table 3.

Based on the mixing ratio of the experimental waste and calorific values, it was calculated that ‘waste 4’, ‘waste 5’, ‘waste 6’ and ‘waste 7’ can evolve 1082.5 Wh, 869.4 Wh, 1372 Wh and 553.86 Wh of energy up on incineration. As ‘waste 4’ has 72.2% of moisture content so it required 497.69 Wh of energy to fully dried up for combustion. Similarly, ‘waste 5’, ‘waste 6’ and ‘waste 7’ has moisture content 77%, 60.8% and 81.9% which required 482.52 Wh, 381 Wh and 513.23 Wh of energy. But for ‘waste 4’ on 70 liters of hydrogen is given as a fuel assisted incineration process which is equal to 210 Wh of energy. This means that 53.58% less energy is given to ‘waste 4’ to initiate incineration process based on its moisture content. On similar grounds ‘waste 5’ of moisture content 77% was given 57.72% less energy with 68 liters of hydrogen, ‘waste 6’ of moisture content 60.8% was given 68.5% less energy with 132 litres of hydrogen and waste 7 with 81.9% moisture content was given 56.7% less energy with 244 litres of hydrogen.

TABLE 4. Reduction in weight of waste and LOI after incineration.

Batch Number	Initial Moisture Content %	Amount of waste (gram)	Residue Left (gram)	Reduction in weight %	Loss on ignition %
Waste 1	87	1000	111.2	88.88	1.74
Waste 2	60	1000	28.6	97.14	2.80
Waste 3	90	1500	52	96.50	6.41
Waste 4	72.2	1100	90.2	91.80	6.12
Waste 5	77	1000	136	86.41	5.38
Waste 6	60.8	1000	87.6	91.24	2.97
Waste 7	81.9	1000	54.8	94.52	3.72

C. RESIDUE ANALYSIS

The residue after incineration has been collected and tested for its LOI. Figure 9 shows the residues left for all the homogeneous and heterogeneous waste batches. The detailed parameters have been presented in table 4. The weight reduction has been calculated to be 88.88%, 97.14%, 96.50%, 91.80%, 86.41%, 91.80% and 94.52% for the batches waste 1 to 7 respectively which is in high agreement with the standard reduction values for incineration i.e., between 75%–90% [46], [47].

Further, it has been observed that wastes with more moisture content were reduced less in weight as compared to low moisture content waste. The LOI values have been calculated for all the waste batches using a high-temperature furnace as explained in the above section (materials and method). The calculated values for batches of waste 1-7 were 1.74%, 2.80%, 6.41%, 6.12%, 5.38%, 2.97%, and 3.72% respectively which lies within the standard LOI values i.e., between 2 – 6% [46]. The residue of paper waste (waste 1) showed a minimum LOI value which is due to the high combustibility of paper

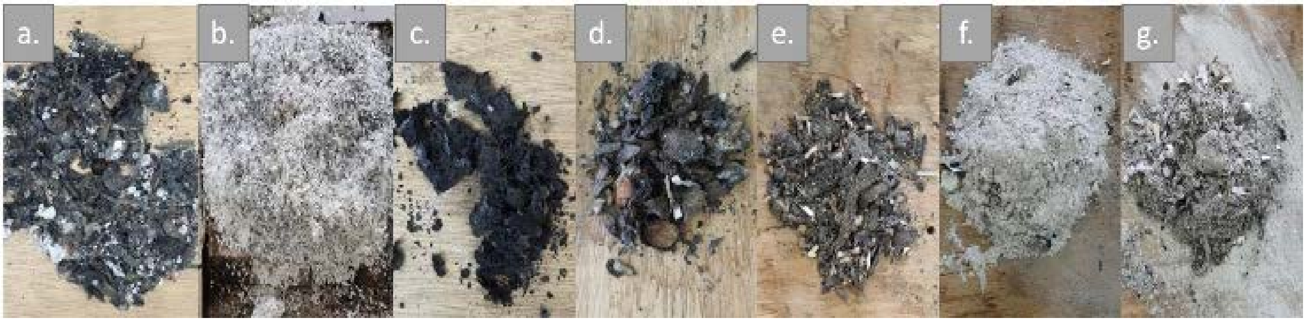

FIGURE 9. Bottom ash for incinerated waste (a) waste 1, (b) waste 2, (c) waste 3, (d) waste 4, (e) waste 5, (f) waste 6, (g) waste 7.

TABLE 5. Comparison of characteristic behavior of current study and reference studies.

Type of Waste	Initial Moisture Content %		Ash Content %		Loss on ignition %		References
	Measured	*Literature*	*Measured*	*Literature*	*Measured*	*Literature*	*Authors*
Food	87	51.4	11.12	[a] 5.5 [b] 10.92	1.74	[a] 6.2	[a] O. Nam-Chol & W. G. Kim [48] [b] Götze et al [49]
Paper	60	3.5	2.86	[a] 10.7 [b] 8.1	2.80	[a] 14.2	[a] O. Nam-Chol & W. G. Kim [48] [b] Götze et al [49]
Textile	90	N/A	3.5	[b] 9.2	6.41	N/A	[b] Götze et al [49]

waste. The residue of food waste (waste 2) showed the second lowest value of LOI whereas, textile waste (waste 3) shows the highest value of LOI (6.41%). This can be due to unusual moisture content in waste (90%).

The LOI for waste 4 (containing 500g food waste, 300g textile waste, and 300g paper waste) with 72.2% moisture content showed a 6.12% LOI value which is due to the high percentage of hard to incinerate food waste (especially watermelon rind, etc.). Waste 5 (containing 400g food waste, 300g textile waste, and 300g paper waste) showed a bit less 5.38% LOI value than waste 4. This was due to the absence of hard crust food waste. However, waste 6 & waste 7 showed lower LOI values of 2.97% and 3.72% with the moisture content of 60.8% and 81.9% respectively. This is due to the type of food waste present and less moisture content. It can be inferred from the results that the type of waste may affect the incineration performance. Furthermore, the moisture content of around 80% can be handled by the presented design. However, waste with a moisture content of more than 90% reduces the incineration performance.

D. COMPARATIVE ANALYSIS FROM LITERATURE

The results of the current study's characterization were compared to studies done for the incineration of various waste types in the literature. Experiments performed in all these studies use different batches of waste ranging 1 to 1.5kg of weight [48]. A summary of this comparative analysis of current study with literature is summarized in table 5. It was noted that the moisture content in the current study was higher. This was due to the waste being given more moisture as part of the current study to examine the typical behaviour of incineration for waste with a high moisture content. Results shows that ash content% for food waste was a bit high (11.12%) from literature studies. But loss on ignition was much less (1.74%) as compared to literature (6.2%). In case of paper and textile waste ash content is quite low (2.86%) compare to previous studies. Similar behaviour for loss on ignition in incineration of paper and textile waste was observed in current studies compared to earlier studies.

IV. CONCLUSION

Green and sustainable fuels are necessary for sustainable waste management. In this study, a systematic investigation has been presented to examine the feasibility of hydrogen as the primary fuel for waste management. A shaft-type waste incineration chamber has been used which was fitted with specially designed burners. A pre-mixture of hydrogen and oxygen in a stoichiometric ratio has been fed to the burners and burners have been properly arranged for homogenous heat distribution. Diverse combinations of solid waste, including food, textiles, and paper, have been used with different moisture concentrations. A maximum temperature of 850°C for MSW (containing food, textile, and paper waste) with 77% moisture content has been recorded. A total of 68liters of hydrogen has been consumed for 1kg MSW which translates to 204Wh of energy being consumed. Similarly results further concludes that more hydrogen and time was required with waste of high moisture content. Also reduction in weight and LOI of all samples of treated waste have been calculated to be within 86-94% and 1.74%-6.41% respectively which satisfy the incineration performance. The system worked efficiently for diverse MSW with a maximum moisture content of approximately 80%. The optimum performance at high moisture content can be correlated with the characteristic high-temperature (i.e., 2800°C) and a concentrated flame of hydrogen. However, increasing the moisture content to 90% reduces performance.

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