Industrial and Domestic Waste Management

Research Article
Volume 3(2), 2023, 115–126
https://doi.org/10.53623/idwm.v3i2.349

Sustainable Energy from Waste: A Feasibility Study in Miri, Malaysia

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SUBMITTED: 3 November 2023; REVISED: 11 December 2023; ACCEPTED: 14 December 2023

ABSTRACT: The growth of urban populations, industrialization, and economic development has led to a surge in solid waste production. When local recycling infrastructure falls short, much of this waste ends up in landfills, causing environmental and social challenges. This study aims to assess the feasibility of converting municipal solid waste (MSW) into energy, with a focus on combustion chamber modeling in Miri, Sarawak. Data on MSW composition are obtained from secondary sources. Ansys Fluent software is used to model the combustion chamber, and simulations are conducted to explore temperature, turbulence, and species distribution. MSW composition illustrates higher substantial fractions, with 39.8% being food waste, followed by 20.7% plastic/rubber. Calorific values range from 4652 kJ/kg for food waste to 32564 kJ/kg for plastic/rubber. Combustion simulations result in maximum flue gas temperatures of 1500 °C, 1200 °C, and 1800 °C under varying air inlet conditions. Turbulence intensities on the grate range from 125% to 174% for these air inlet configurations. The study concludes that moisture content significantly affects calorific value and heat generation during combustion. Higher turbulence intensities lead to increased reaction rates and heat generation, improving the energy efficiency of the process.

KEYWORDS: Waste-to-energy; municipal solid waste; solid waste management; sustainable energy

1. Introduction

Waste to Energy (WTE) is the process of generating energy, typically in the form of heat or electricity, through the primary treatment of solid waste. Solid waste is defined as any unwanted, surplus, rejected, abandoned, or discarded material. In recent years, WTE technology has garnered increased attention in many countries, primarily due to population growth. Worldwide urbanization, industrialization, improved living standards, population growth, and economic development have significantly contributed to the rise in solid waste production. Therefore, when the production of solid waste exceeds the local recycling management capacity, a significant portion of the waste ends up being deposited in landfills. In literature, 37% of Municipal Solid Waste (MSW) is disposed of in landfills, 33% is dumped in an open environment, 11% of MSW is incinerated, and 19% is recovered through recycling and composting [1]. In developing countries like Malaysia, landfilling is the most commonly used method for disposing of unwanted waste due to its simplicity and cost-effectiveness when compared to recycling. However, due to waste degradation and rainwater percolation through decomposed wastes, landfills often generate leachate. Leachate is produced when the high moisture content in landfill wastes overflows through porous materials. The composition of leachate includes biodegradable organic matter, humid and fulvic acids, heavy metals, nitrogenous matter, and chlorinated organics [2].

Landfill leachate can pose significant risks to adjacent habitats over extended periods [3]. While landfills are the primary contributors to leachate production, it is essential to consider treating or filtering leachate before releasing it into the environment. Unfortunately, many uncontrolled landfills in Malaysia lack essential components such as bottom liners and leachate collection or treatment systems. Malaysia has a total of 146 operated landfills and 165 non-operated landfills. However, only 18 of the operated landfills are equipped with leachate control and treatment systems, meeting the criteria for sanitary landfills [4]. On the other hand, non-sanitary landfills, lacking a leachate catchment liner system, allow untreated leachate to percolate into the soil and groundwater. Despite the environmental and social problems associated with landfills, it is a critical issue that demands immediate action to prevent permanent impacts on the environment and public health. To address this, WTE technology is essential for more efficient MSW management. This technology is a well-established approach adopted by many countries to reduce MSW landfills and generate energy simultaneously. It involves using MSW as a feedstock to produce energy. As a result, using WTE plants to consume MSW can significantly reduce landfill waste and the need for new landfills. Importantly, WTE technology provides an environmentally friendly alternative to fossil fuels for energy generation. Currently, there is limited research on the implementation of WTE plants in Miri, Sarawak, with most literature focusing on overseas case studies. Furthermore, research on mass combustion is prevalent, while modular WTE plants receive little attention. Therefore, the purpose of this research is to bridge these gaps by conducting a feasibility case study in Miri to develop a portable WTE plant.

2. Materials and Methods

2.1. Municipal Solid Waste.

To ascertain the heat generated through the combustion of MSW, it is necessary to first determine the quantity of MSW. For the feasibility study on developing a WTE plant in Miri, data on MSW composition (% by weight) and calorific value (kJ/kg) in Miri were collected from secondary sources. The data sources were compiled through comprehensive literature reviews from reputable publishers, including Elsevier, Springer, Wiley, Taylor & Francis, and the Web of Science.

2.2. Ansys fluent modelling.

The model was sketched out, and then the extrude function was used to transform the 2D sketch into a 3D representation of the internal part of the combustion chamber. The thickness of the extrusion was set to 5 meters, corresponding to the width of the combustion chamber. The grate consisted of staircase-shaped panels with a downward slope (grade) of 0.43, a vertical height of 0.3 meters, and a horizontal length of 0.7 meters for each section.

The extrusion function was also employed to create openings in the bottom surface of the grate. These openings served as the primary air inlets, with each having a diameter of 0.1 meters. Preheated air was injected through these openings into the combustion chamber. Each secondary air inlet had an opening with a diameter of 0.1 m. There were two secondary inlets, one located at the top of the waste inlet to the incinerator section and the other at the top of the grate incinerator. Preheated secondary air was injected through these openings to promote more complete combustion in the secondary combustion chamber.

The mesh was generated using the Ansys meshing function, designed with the final mesh consisting of 511,676 elements and 98,403 nodes. A total of five boundary conditions were considered for modeling, which included primary and secondary air inlet, waste inlet, bottom ash outlet, and flue gas outlet.

3. Results and Discussion

3.1. MSW composition and calorific value.

The data presented in Table 1 were collected from various bins in Miri town, with bin sizes ranging from 65 liters (l), 120l, 240l, 660l, 1100l to 1500l. The collection of Municipal Solid Waste (MSW) was the responsibility of local authorities, and the frequency of MSW collection varied according to contractual terms. Tang [5] divided Miri into urban and rural areas, with daily MSW collection in the urban area and 2 to 3 times weekly collection in the rural area.

Table 1. Miri MSW compositions [5].

Waste composition	% of weight	Calorific value (kj/kg)
Food waste	39.8	4652
Paper	14.2	16747.2
Plastic/rubber	20.7	32564
Metal	3.4	697.8
Wood	0.5	18608
Glass	2.8	139.6
Textiles	4.3	17445
Miscellaneous	14.3	6978

In modeling the combustion chamber, we assumed the use of proximate and ultimate analysis data based on the MSW produced in Miri. Proximate analysis helps determine the proportion of a fuel that burns in a gaseous form, while ultimate analysis provides information on the mass fractions of carbon, hydrogen, oxygen, nitrogen, and sulfur within the MSW. According to Kusumastuti et al. [6], the proximate analysis results were as follows: 0.2% volatile, 0.2% fixed carbon, 0.1% ash, and 0.5% moisture. They also reported the ultimate analysis, which indicated: 0.5% carbon, 0.1% hydrogen, 0.3% oxygen, 0.05% nitrogen, and 0.05% sulfur.

In Table 1, the calorific value for food waste is approximately 4652 kJ/kg, which can be considered relatively low. This can be attributed to the high moisture content typically found in food waste [7]. Dry food waste, such as bread crumbs and leftover cookies, exhibits higher calorific values compared to wet food waste, including kitchen residuals, fruit peels, and organic waste. The moisture content within the MSW necessitates additional energy to extract water content through the evaporation process, which can hinder effective heat generation during combustion [8]. However, food waste also contributes to water vapor formation inside the combustion chamber, which enhances heat transfer between the flue gas and the boiler. Water vapor serves as an effective heating medium due to its release of latent heat upon condensation at a constant temperature [9, 10]. Consequently, managing the portion of food waste entering the combustion chamber is essential for optimizing combustion.

The calorific values for paper, wood, and textiles were 16747.2 kJ/kg, 18608 kJ/kg, and 17445 kJ/kg, respectively. These materials can be grouped together because their raw materials are sourced from trees, resulting in an average calorific value of approximately 1500 kJ/kg. Among them, paper yields the lowest heat energy during combustion but has a low ignition point, making it easily combustible with minimal heat. This makes paper an essential component for initiating combustion within the incinerator. Even distribution of paper in the combustion chamber within the MSW piles enhances uniform combustion, aids in the removal of moisture content, and prepares MSW for efficient combustion.

3.2 Static temperature and turbulence intensity.

The heat produced by the designed waste-to-energy (WTE) plant was evaluated. Static temperatures in the combustion chamber were studied under three different scenarios (Figure 1): (a) the burner operated with primary air only, (b) the burner operated with secondary air only, and (c) combustion with both primary and secondary air. The combustion mode was set to non-premixed combustion, where the fuel and oxidizer were introduced separately into the combustion chamber.

To simulate the actual composition of municipal solid waste (MSW) collections, the software incorporated a coal calculator by inputting the properties of the MSW. The operating pressure was set to 101,325 Pa, and the calorific value of MSW was set to 1.28e7 J/kg. In Figure 1(a), primary air was injected into the combustion chamber through the grate, with the maximum temperature near the top of the furnace ranging from 1500 °C to 1300 °C. The temperature at the primary air inlet, located at the grate, was observed to be lower than the surroundings. This lower temperature resulted from the high-speed air injection needed to create turbulence in that area [11, 12]. The airspeed at the primary air inlet was approximately 9 m/s, and this high-speed injection caused a cooling effect in that specific region [13]. In Figure 1(b), the highest temperatures observed ranged from 1200 °C to 930 °C. Figure 1(c) resulted in the highest combustion temperature, reaching 1800 °C to 1650 °C at the flue gas outlet chamber. The presence of both primary and secondary air inlets is crucial for converting MSW into heat energy for electricity generation [14, 15]. The dual air inlets encourage better mixing of MSW with oxygen during the combustion process [16, 17].

Attaining specific temperatures highly depended on the turbulence created within the incinerator [18, 19]. The turbulence patterns of the combustion chamber were studied using the k-epsilon turbulence model, and the results are presented in Figures 2. Figure 2(a) clearly showed turbulence formation above the grate surface, with turbulence intensity at approximately 125%. The turbulence began to dissipate at the flue gas output channel. When using secondary air (Figure 2(b)), turbulence was primarily concentrated around the secondary air nozzle, at about 136% intensity. The surrounding area of the combustion chamber exhibited turbulence with an intensity ranging from 40% to 80%. In the third condition (Figure 2(c)), which included both primary and secondary air, turbulence was distributed more evenly throughout the primary and secondary combustion chambers, with intensity levels around

174% at the secondary air nozzle, 158% at the primary air nozzle, and 98% in the surrounding area of the incinerator.

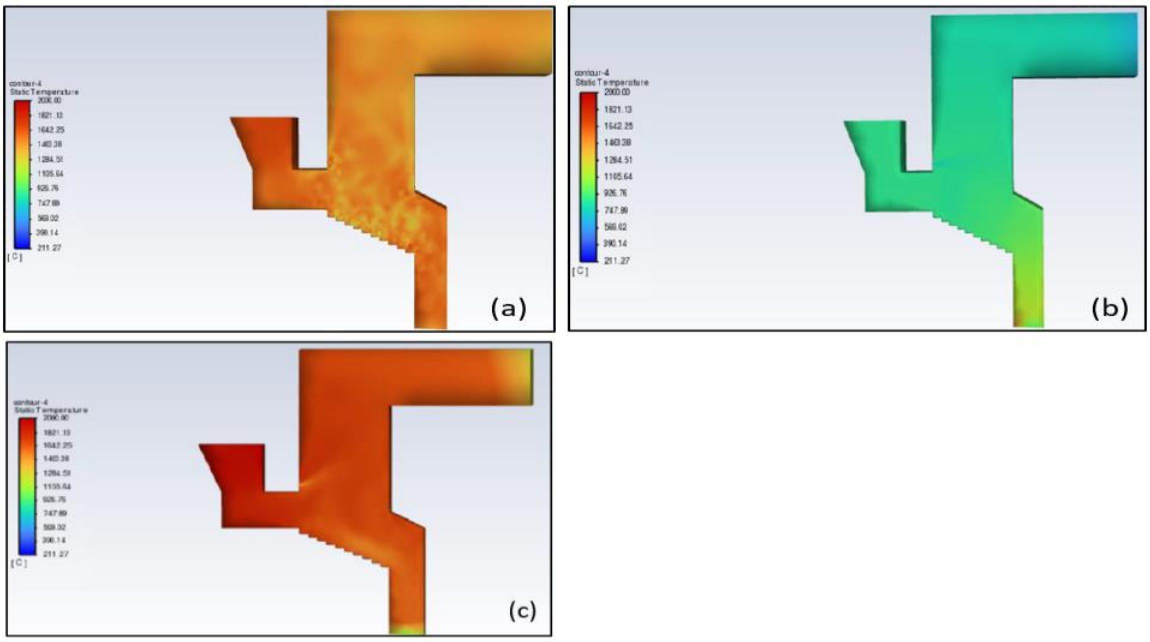

Figure 1. Static temperature with primary air (a), secondary air (b), and primary and secondary air (c).

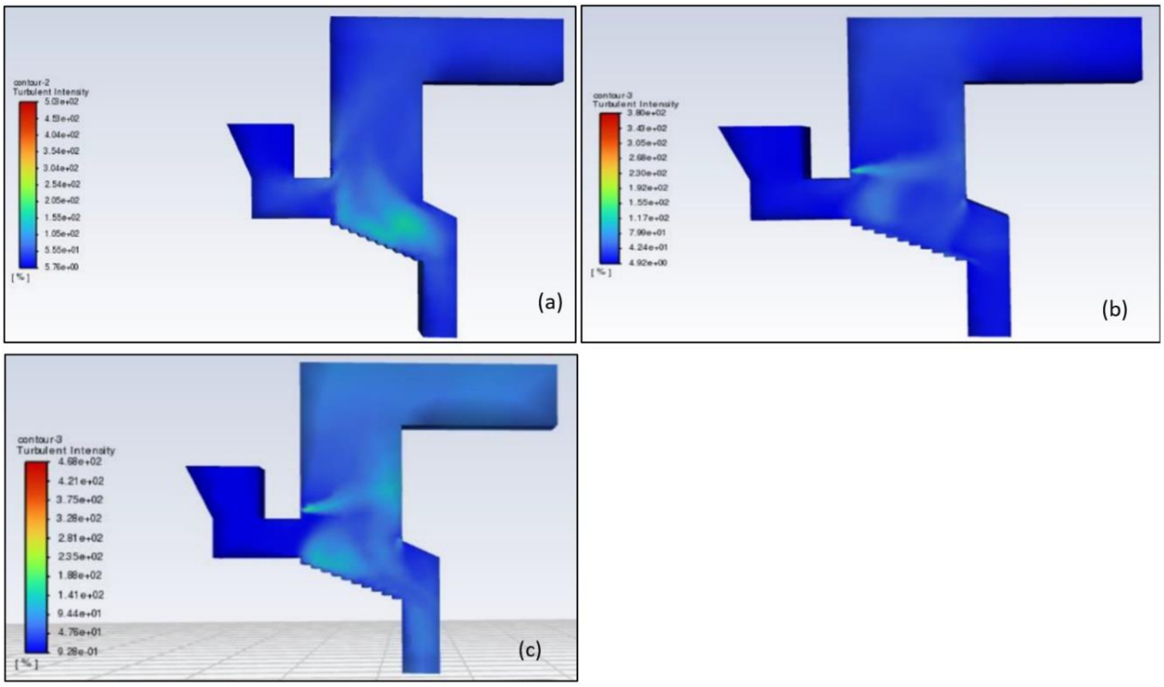

Figure 2. Turbulence intensity with primary air (a), secondary air (b), and primary and secondary air (c).

3.3 Species mass fraction.

The species concentration was studied to identify the reactions within the combustion chamber. Among all the conditions, the primary and secondary air inlets produced better combustion results. The constant injection of primary and secondary air can "disturb" the airflow within the incinerator [20], providing more kinetic energy for MSW disintegration to occur [21]. Therefore, the third model, in which primary and secondary air are provided, was chosen for species analysis, and the results are displayed in Figure 3.

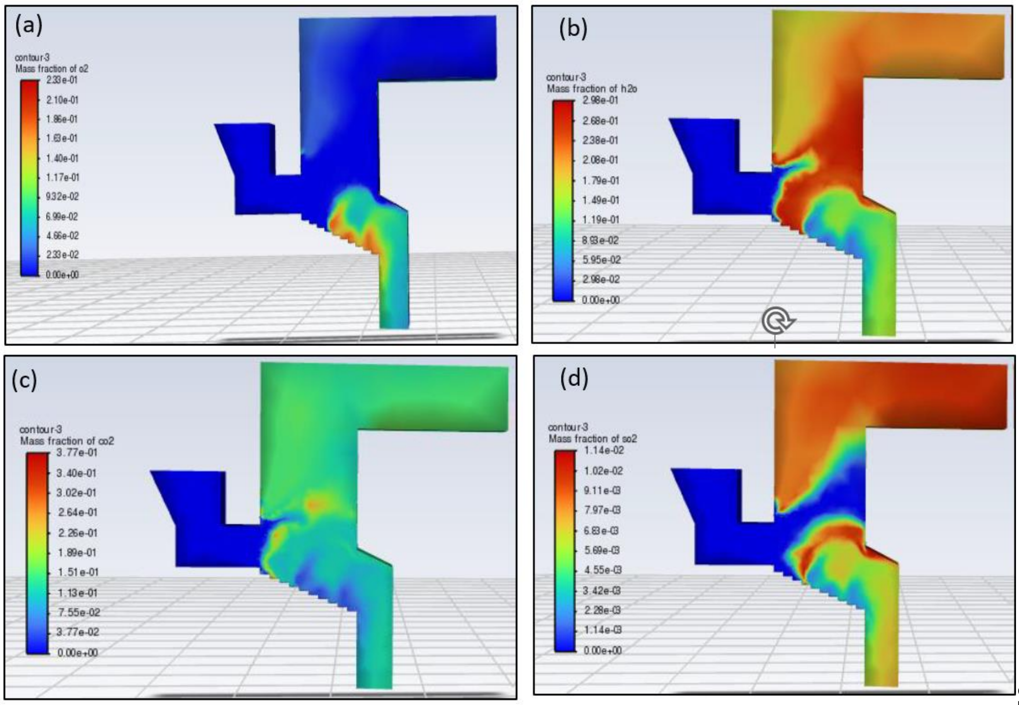

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Figure 3. Mass fraction of oxygen (a), water vapor (b), carbon dioxide (c), sulphur dioxide (d).

In Figure 3(a), the mass fraction of oxygen during the combustion of MSW is presented. In this model, oxygen is injected into the incinerator through underfire and overfire air nozzles, with a high oxygen fraction present on the grate where the MSW is positioned. There is 0.233% of oxygen starting from 2.8m to the right of the grate. This oxygen is consumed during the combustion of MSW, producing carbon dioxide, water vapor, and energy in the form of heat and light [22]. At this point, the MSW is almost completely broken down due to combustion in that area, and any remaining oxygen will diffuse to other parts of the combustion chamber with lower oxygen concentrations for further combustion. Additionally, there is a small fraction of oxygen observed at the secondary air inlet, approximately 0.05%, due to aggressive combustion occurring at the front end of the grate where the MSW is being fed [23]. Figure 3(b) illustrates the formation of water vapor within the combustion chamber. Steam is actively generated at the secondary air inlet and within the initial 2.8m of the grate. The results obtained indicate that 0.3% of water vapor formed at the primary and secondary nozzles, which combustion is expected to be more aggressive. However, combustion activity is less pronounced in the remaining 4.2m of the grate, with only 0.15% of water vapor being formed in that area [24]. This observation is attributed to the moisture content within the MSW, which is converted into water vapor at the 2.8m of the grate. At this stage, the MSW is completely dried out and pushed down for further combustion along the remaining 4.8m, where char and soot will form and collect at the bottom ash outlet. Figure 3(c) displays the mass fraction of carbon dioxide formed inside the combustion chamber. Carbon dioxide is produced as a result of the reaction between the carbon content within the MSW and oxygen during the combustion process. The formation of carbon dioxide was evenly distributed within the combustion chamber, with a mass fraction ranging from 0.15% to 0.19%. During combustion, sulphur dioxide was also generated when sulphur content in MSW reacts with oxygen [25]. Sulphur dioxide is considered a highly toxic element that can negatively impact human health and the environment. Consequently, most WTE plants are equipped with wet bag filters to capture all toxic elements in the flue gas before it is released into the environment. In Figure 3(d), the contour of the mass fraction of sulphur dioxide formation is shown. A significant fraction was detected at the top of the flue gas output channel, approximately 0.01%. The sulphur dioxide fraction at the secondary and grate air inlets is 0.008% and 0.0055%, respectively.

3.4 Oxygen mass fraction under different air inlet temperature.

The effect of different air inlet temperatures on the breakdown of MSW was studied using the combustion method. Different types of air inlets temperature which are 300 °C, 400 °C, and 500 °C are simulated and the mass fraction of raw material and product are recorded in Figure 4. The pattern of the graph illustrated that the mass of oxygen is reduced across the length of the grate. Oxygen is used for the combustion of MSW to break down the complex structure of MSW into sub-products, which the oxygen concentration decreased over the length of the grate. In Figure 4(a), both primary and secondary air inlets are set to 300 °C, the oxygen mass fraction is starting from 0.22 - 0.24 % and ends with 0.16 - 0.18 % and the end point of grate. For air temperature of 400 °C, Figures 4(b) has showed the mass fraction oxygen at waste inlet is 6×10^{-10} %, sudden surge at the grate length of 2.6m with 8×10^{-10} % of oxygen, and 5×10^{-10} % at the end of grate.

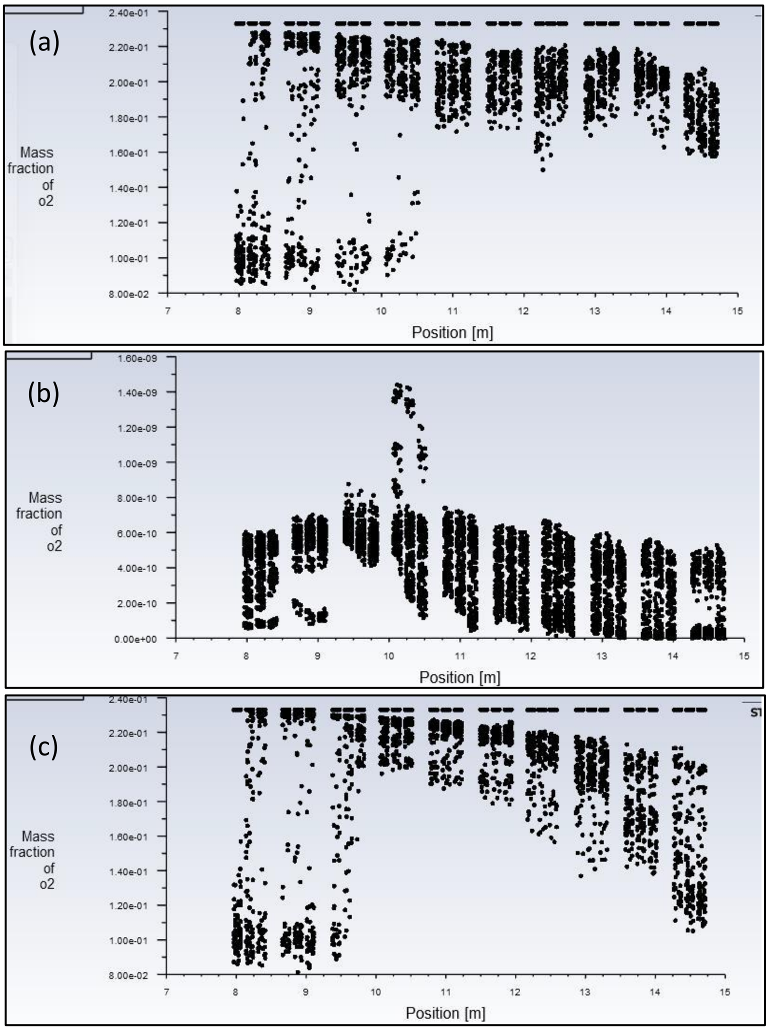

Figure 4.4. Mass fraction of oxygen with primary and secondary inlet air temperature of 300 °C (a), 400 °C (b), and 500 °C (c).

Although the trend of mass fraction of oxygen is reasonable, the value is considered too low compared to air inlet 300 °C previously. Emission is suspected for this part of data due to low mass fraction of oxygen obtained causing low oxygen portion allocated at primary air inlet during the simulation setup stage [26]. Figure 4(c) shows the mass fraction of oxygen for air inlet temperature of 500 °C. Oxygen mass fraction starts with 0.24 % and ends with 0.11 % on grate where increasing temperature increases showed the second peak value gradually increases, while the first peak value decreases. This is due to the higher combustion rate and earlier MSW ignition caused by the higher air temperature resulting, the volatiles will ignite and burn in the primary zone more quickly and use more oxygen [27]. Less oxygen will be present in the main zone, resulting in deeper oxygen-short combustion.

3.5 Water vapour mass fraction under different air inlet temperature.

Figure 5 shows the formation of water vapour under different air inlets temperatures. At air temperature 300 °C, 0.01% of water vapour formed at 0 to 0.7m of the grate. The sudden surge of water vapour formation happens on 1.4m to 4.9m of the grate. The possible reason is due to the moisture content within the MSW is reduced starting from 1.4m. As the water within the MSW has reached it boiling point of 100 °C for water, it turns into water vapour.

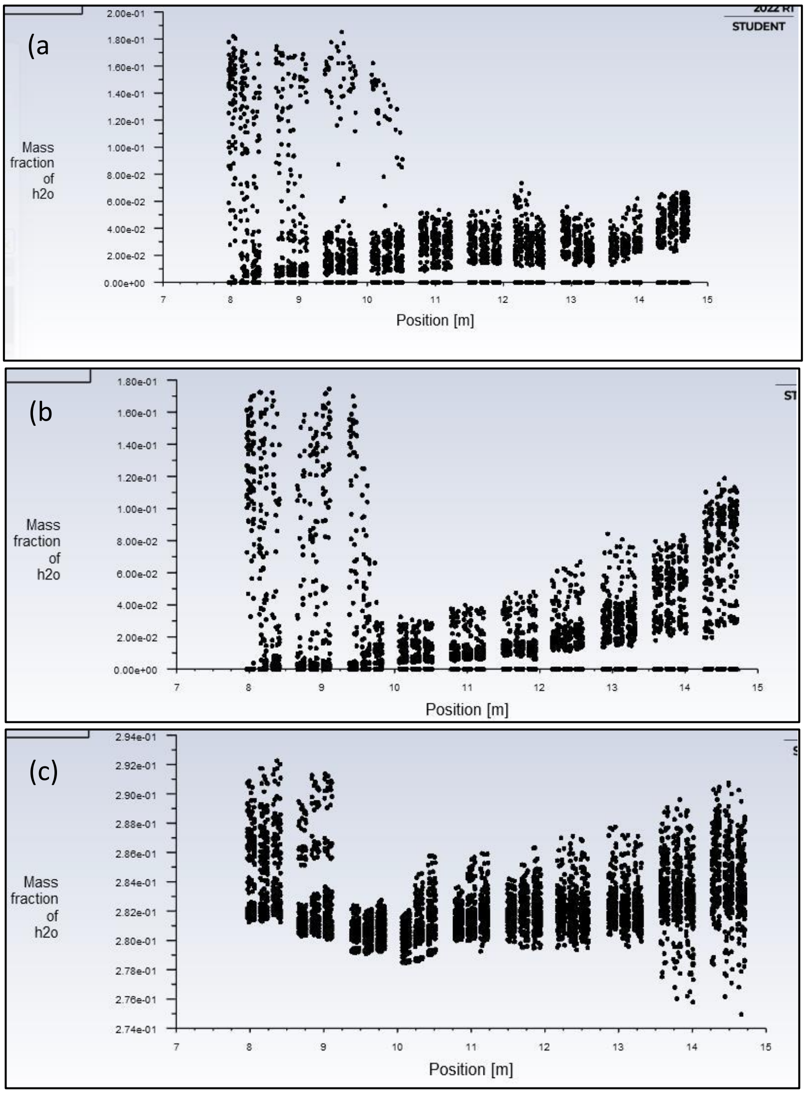

Figure 5. Mass fraction of water vapour with primary and secondary inlet air temperature of 300 °C (a), 400 °C (b), and 500 °C (c).

The energy generated during incineration will be impacted by the moisture content of the MSW feedstock [24]. The exposure of MSW to rain have led the increased moisture content in organic compounds, moist textiles, and food residue. As air temperature increased to 400 °C, the gradient of the curve of the formation of water vapour becomes steeper. The vapour does not form during starting of the grate but increase significantly in the following grate from 0.3 m to 7 m. At the end of the grate where MSW is expected to be completely burn out, 0.11% of water vapour is formed and the gradient is about 0.15%. The water vapour is already form in the entrance of the MSW at 500 °C. The mass fraction of water vapour encounter downgrade from initial MSW inlet until 2.8 m of the grate and start to rebound with an upgrade from 2.8 m to the end of grate. The possible reason for the rebound of water vapour at 2.8 m to 7 m to be occurred is the further breakdown of remaining H_2 molecules to formed H_2O [24]. There are also possibilities of accumulation of water vapour at the incinerator wall and drips back to the grate to be react again [28].

3.5 Challenges in WTE application.

The increasing volume of organic content, requiring proper disposal, has become a significant concern. Currently, there is potential for generating electricity from waste through the management of large-scale biomass using integrated technology. However, transitioning wet-waste conversion technologies from pilot or laboratory settings to commercial applications presents challenges that demand a careful approach. Optimizing larger systems requires comprehensive knowledge, encompassing reactor designs, process configurations, and operational parameters. Successful technology transfer and commercial viability hinge on bridging the gap between lab-scale research and real-world implementation, achieved through modeling studies and pilot-scale validation. To enhance upscaling effectiveness and reliability, incorporating real-time data and feedback loops from commercial-scale operations is crucial for refining predictive capabilities and process models.

Waste-to-Energy faces a series of challenges, with environmental concerns, particularly air emissions, taking the lead. WTE facilities emit pollutants, including greenhouse gases, creating a dual challenge of energy production and environmental impact. Striking a balance to mitigate these emissions while ensuring efficient energy production is a critical challenge. Technological efficiency is also a concern, with a pressing need for economically viable processes that convert waste to energy in an environmentally responsible manner. The variability in waste composition further complicates matters, impacting the stability of energy output. Public perception, often influenced by worries about air quality and associated health risks, poses a significant hurdle. Navigating stringent regulatory landscapes adds complexity to the development and operation of WTE facilities, requiring a careful balance between innovation and compliance, especially regarding air emissions.

Despite these challenges, WTE holds promise, particularly in addressing concerns related to air emissions. Serving as a renewable energy source, WTE contributes to reducing reliance on fossil fuels and aligns with sustainable energy practices. Beyond energy production, it plays a crucial role in waste reduction and resource recovery, promoting a circular economy. Integrating WTE into comprehensive waste management strategies not only provides economic benefits, such as job creation and local economic stimulation but also offers an opportunity to address concerns about air quality and emissions. Ongoing technological advancements in WTE provide hope for improved efficiency and reduced environmental impact, positioning it as a crucial player in the evolving landscape of sustainable waste management and renewable energy generation, with a heightened focus on mitigating air emissions.

4. Conclusions

This study aimed to assess the feasibility of establishing a portable waste-to-energy plant in Miri. The composition of municipal solid waste (MSW) in Miri revealed that the majority of the waste was attributed to food waste, accounting for 39.8% of the total daily waste production rate of 281 tons. Calorific values for various MSW components were determined, showing that food waste had a calorific value of 4652 kJ/kg, while paper had 16747.2 kJ/kg, plastic/rubber 32564 kJ/kg, metal 687.8 kJ/kg, wood 18608 kJ/kg, glass 139.56 kJ/kg, textiles 17445 kJ/kg, and miscellaneous items 6978 kJ/kg. The moisture content within the MSW had a significant impact on these values, influencing heat generation during combustion. Simulations were conducted to predict static temperature and turbulence intensity within the combustion chamber. The findings revealed that the highest flue gas temperatures were observed at 1500°C for the primary air inlet, 1200 °C for the secondary air inlet, and 1800°C when both primary and secondary air inlets were used simultaneously. This increase in temperature was attributed to the higher oxygen concentration resulting from a greater number of primary air inlet nozzles. Additionally, simulations were performed to examine the mass fraction of different species within the combustion chamber at various air inlet temperatures (300 °C, 400 °C, and 500 °C), focusing on oxygen and water vapor. The results indicated that oxygen concentration decreased as temperature increased due to faster combustion rates. The formation of water vapor was notably influenced by air inlet temperatures.

Acknowledgments

The authors thank Curtin Universiti Malaysia, State Development Office of Terengganu Malaysia, and Chinhoyi University of Technology Zimbabwe for facilitating this work.

Competing Interest

The authors declare no conflict of interest.

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