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Microwave Co-pyrolysis on Plastic and Sludge Waste: Effect of Heating Insulation on Product Yield

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The surge in global waste production strains waste management systems, where plastics made from polyethylene terephthalate (PET) and sludge waste pose significant environmental threats. Microwave pyrolysis offers a promising solution by converting waste into valuable products. The main advantages and disadvantages of microwave irradiation are the rapid heating during operation and significant heat loss during idle conditions. Microwave rays emitted by a magnetron undergo pulse operation on an on-off basis. The capability of the reactor setup and feedstock properties to retain and prevent heat loss during idle conditions is important to ensure effective thermal decomposition. Statements regarding the energy efficiency of microwave heating may be subject to scrutiny if the microwave needs to be operated for extended durations to offset heat dissipation. In this work, a microwave-powered pyrolysis system is designed with and without insulation. A feedstock mixture comprised of PET and sludge (1:1 mass ratio) is being thermally degraded and the degree of decomposition will be measured through the bio-char yield, which will be compared with the mass loss data from the thermogravimetric analysis (TGA). The discrepancies between both values indicate the possibility of incomplete decomposition with speculations of 1. Insufficient operation period and/or 2. Ineffective heat insulation. Results reveal the insulation of having a ceramic blanket wrapping the entire reactor during operation (Setup 2) was the most effective as it can achieve the highest temperature (557.19 °C) and heating rates (28.53 °C/min) with minor heat loss (29 °C/min), resulting in a more stable temperature profile. Setup 1 (with only fibreglass insulation) and Setup 3 (without insulation) report lower maximum temperatures (470.57 °C and 391.11 °C), lower heating rates (~23.9 °C/min) and unstable temperature profiles as compared to Setup 2. The average solid yield obtained at a pyrolysis temperature of 500 °C is around 39.05 wt.%, higher than those reported from TGA (26.01 wt.%) indicating that the current setup still requires optimization. Setup 2 presents the lowest solid yield at an improved decomposition, owing to the better insulation setup. This study reveals that despite the good performance of microwave heating, insulation also plays a vital role in ensuring effective decomposition.

1. Introduction

A global problem arising from the industrial revolution is the overwhelming generation of waste. Plastic waste like Polyethylene Terephthalate (PET) is widely used in packaging due to its favourable properties such as durability, low cost, and versatility. The non-biodegradability and low recycling rate of PET have raised serious environmental concerns, affecting ecosystems and human health (Ahmed, 2023). Sewage sludge is a by-product of wastewater treatment that contains significant amounts of organic and inorganic materials. The rapid industrialization process increased sewage generation from the industry, which is currently disposed of through landfilling or incineration (Racek et al., 2020). These management methods are not sustainable and may further degrade the natural environment. Thermochemical conversion methods are proposed for waste management as they facilitate volume reduction, resource recovery, energy production, waste valorization, and environmental

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benefits through the transformation of waste materials into valuable products like biochar, syngas, and bioliquids (Nandhini et al., 2022). Pyrolysis is a thermochemical conversion method that is suitable for treating and valorizing these wastes into value-added products (Mong et al., 2021). Pyrolysis of PET can break down the polymer into simpler molecules, producing chemicals, and other value-added products (Bungay, 2017). This process can reduce the amount of PET waste in landfills and the environment while providing an alternative source of energy and raw materials. The pyrolysis of PET waste has several potential downsides. The quality of the pyrolysis products produced might be less desirable due to incomplete decomposition and the formation of undesirable by-products as reported by Jia et al. (2020). For sludge pyrolysis, the derived biochar might contain toxic heavy metals and prevent direct usage. Wan et al. (2022) reported the content of Cadmium (Cd) in the biochar from sludge pyrolysis to be at 12.64 mg/kg. Co-pyrolysis is a possible solution to overcome such drawbacks. Mohamed and Li (2023) conducted co-pyrolysis of sewage sludge with a non-biomass feedstock and reported a reduction in water, oxygen, and nitrogen contents of bioliquids which indicated co-pyrolysis can produce a higher quality of oil product and lower the activation energy and enthalpy and so less energy is required to break down the feedstock materials. Sludge can act as a catalyst-cum-feedstock for the pyrolysis of PET waste by providing a synergistic effect.

Conventional heating is normally used in pyrolysis but with the downside of heat transfer limitation and low heating rate. Microwave heating is an emerging technology that provides rapid and volumetric heating of the feedstock, resulting in faster reaction rates and reduced residence times compared to conventional pyrolysis (CP). Microwave pyrolysis (MP) is energy-efficient when compared with CP as it directly heats the feedstock through dielectric heating, creating hot spots due to uneven microwave energy distribution (Prakash et al., 2015). A higher purity bio-oil with the absence of harmful compounds like heavy polycyclic aromatic compounds (PAH) could be produced during MP and has been reported by Mohamed (2018). MP still faces technical challenges in its commercial viability. Heat loss is a major issue leading to the problem of temperature instability. Bartoli et al. (2019) revealed that different materials would have different thermal conductivity. For example, metals are high thermal conductivity materials so they may transfer heat more readily to the reactor's wall, leading to increased heat loss. The effective operation of MP systems relies on proficient heat transfer control within the reactor, which depends on selecting and using appropriate insulation materials. An optimal insulation material for MP must exhibit high microwave transparency at operational temperatures, to minimize heat loss, achieve uniform heating, and maintain ideal reaction conditions within the pyrolysis reactor (Yang et al., 2023). Some insulation materials that are currently being used in the industry are glass wool and ceramic fibres. Glass wool is composed of fine fibres of glass. It is fire-resistant as the glass itself is non-combustible (Jeon et al., 2017). It is also durable, easy to install, and has a low thermal conductivity of 0.023 W/m·°C. However, glass wool is not ideal for microwave pyrolysis (MP) due to its high dielectric loss properties, which causes it to absorb microwave radiation and heat up, potentially leading to overheating and degradation. Glass wool can only withstand temperatures up to 649 °C, limiting its effectiveness in MP processes where higher temperatures are common (Stewart, 2016). It is observed from the work of Prathiba et al. (2018), that the temperature profile of microwave heating shows fluctuations with the use of glass wool insulation. Ceramic fibre is an inorganic fibre, such as alumina-silica. It is lightweight, durable, and heat-resistant (Bilisik and Syduzzaman, 2022). Ceramic fibre has lower dielectric loss properties (3.06) (Tan et al., 2019) compared to glass wool (6.7) (Zhao et al., 2019) , minimizing microwave energy absorption and allowing efficient heating of the feedstock. It can also withstand temperatures up to 1260 °C (Ritonga et al., 2021). Its high thermal shock resistance also helps buffer sudden temperature changes. Compared to glass wool insulation, Wan Mahari et al. (2022) shows that ceramic fibre insulation provides a stable temperature profile with fewer fluctuations during MP. Ceramic fibre can also be considered as one of the potential insulation materials for MP. Therefore, this research project aims to investigate the effect of different insulation materials on the thermal gradient within the reactor, which will directly influence the decomposition of feedstock during MP. PET and sludge will be used as the combined feedstock. Glass wool and ceramic fibres will be experimented as insulation materials.

2. Methodology

The TGA experiment was conducted through a thermogravimetric analyzer (TA Instrument Q500). A fixed amount of 10±0.1 mg sample was subjected to the analyzer, while the nitrogen gas with a high purity of 99.8 % was purged into the reaction chamber to maintain an inert condition for the co-pyrolysis process. The sample was heated from room temperature to 850 °C at the nitrogen gas flow rate of 20 mL/min. The TGA experiment was carried out at 20 °C/min. The weight changes of the sample throughout the TGA experiment were recorded as a function of time and temperature.

PET pellets were collected from a plastic recycling company, Diyou Fibre (M) Sdn. Bhd. located in Nilai, Negeri Sembilan, Malaysia. Industrial sludge was collected from QL Figo (Johor) Sdn Bhd located in Kulai, Johor, Malaysia. Activated Carbon (AC) from coconut shells was used as a microwave absorbent in this experiment.

The AC was dried in the oven at a temperature of 105 °C for 12 h to ensure they were moisture-free. After that, AC was weighed to 100 g and then placed into the quartz reactor as the bottom layer. The PET and sludge were weighed with 5 g and mixed well together before being placed above the AC in the quartz reactor. PET and sludge were mixed at a 1:1 ratio. The height of the feedstock bed was set at a constant value of around 2 cm measured from the bottom of the reactor. Three different insulation setups were experimented with, as described in Figure 1. A fibreglass insulation layer (Setup 1) was used to wrap around the quartz reactor as shown in Figure 1a. A ceramic blanket (Setup 2) was further added to the outside of the fibreglass insulation layer as shown in Figure 1b and a setup without insulation (Setup 3) was also conducted to serve as a control as shown in Figure 1c. Next, the valve of the argon supply was activated and the flow rate of the rotameter was set to 1 L/min. The argon gas flowed through the entire system for 15 min to ensure a completely inert reacting medium once the setup was ready. The argon flow rate was further adjusted and fixed constant at 0.7 L/min, which corresponded to a vapour residence time of 3.94 s (fast pyrolysis). The experimental pyrolysis temperature, 500 °C was set through the PID controller. An external data logger was connected to the temperature logger to record the temperature change during the experiment and further calculate the heating rate of the experiment. The microwave oven and temperature logger were switched on concurrently. The experiment then continued uninterrupted for 40 min. After the experiment ended, the setup was allowed to cool down for an additional 20 min while being exposed to a continuous flow of argon gas. Solid leftovers were collected manually as bio-char, the liquid condensed in the flask was collected as bio-liquid and the uncondensed vapour was collected as pyrolysis gas. After collection, the products were measured to determine the yield.

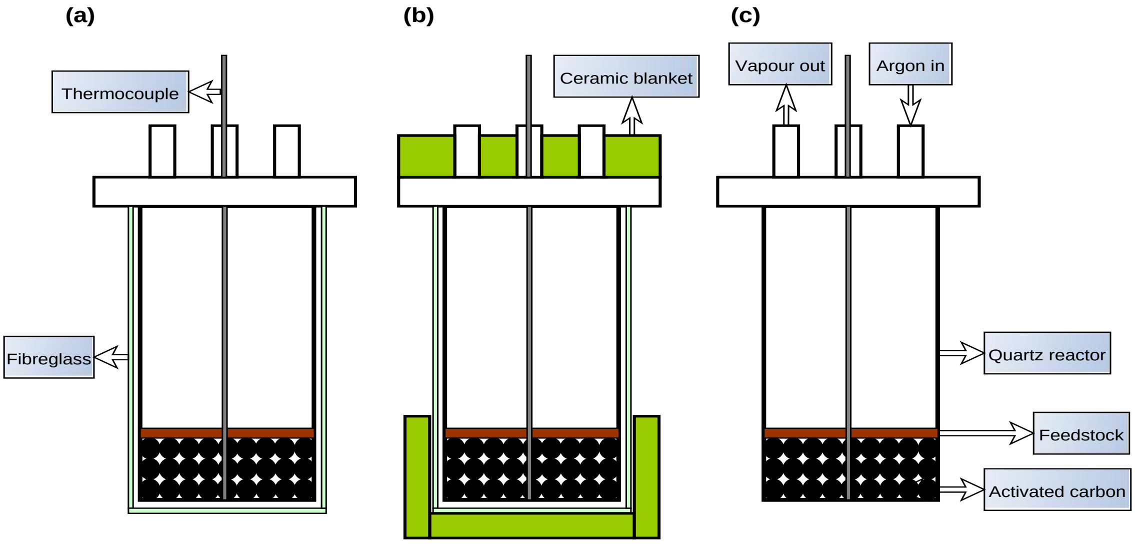

Figure 1: Configuration insulation type of (a) Fibreglass, (b) Fibreglass + Ceramic Blanket, (c) No Insulation

3. Result and Discussion

From Figure 2, the mass loss study has been conducted and can be analysed by the product yields. The product yield of the three main products has been tabulated, which are solid (biochar), liquid (oil), and gas (biogas), the rest of the minor products are sediments and moisture and it will not be included. The highest solid (biochar) yield of 52.65 wt.% was obtained in Setup 3. This was attributed to the low heating rate and average temperature, as shown in Figure 3, which led to incomplete pyrolysis, leaving most of the feedstock as residue (Selvarajoo and Oochit, 2020). In contrast, Setup 2 had the lowest solid yield, 29.75 wt.% and it can be attributed to its strong insulation effect by the thick ceramic blanket layer (Alrasheed, 2023) which caused a lesser heat loss during the experiment compared to Setup 1. It can be claimed that the insulation effect in Setup 2 is better than in Setup 1 due to the dielectric property and the thickness of the layer (Tan et al., 2019; Zhao et al., 2019). Hence, a strong insulation effect would lead to a greater feedstock decomposition rate in the pyrolysis process as the temperature would be more consistent with less heat loss to affect the pyrolysis rate (Qurat ul et al., 2021). From Figure 2, the liquid and gas yield produced from Setup 3 was also the lowest (17.05 wt.%, 7.6 wt.%) due to the lowest temperature during experiments. The relationship between solid yield with liquid and gas yield was proved to be inversely proportional to each other as the higher temperature would increase the liquid and gas yield while decreasing the solid yield and this finding has also been revealed by Qurat ul et al.

(2021). The mass recorded at 500 °C was 26.01 wt.% when the feedstock was pyrolyzed in a TG unit. The value served as a reference on the extent of decomposition as the mass utilized for TGA is much smaller (around a few mg), so heat transfer limitation will be minimal. The char yield of 29.75 wt.% for Setup 2 is very close to the value from TGA, indicating the possibility of total decomposition for the current pyrolysis parameters. It can be claimed that the insulation on the MP setup does play a vital role in the effective decomposition of feedstock.

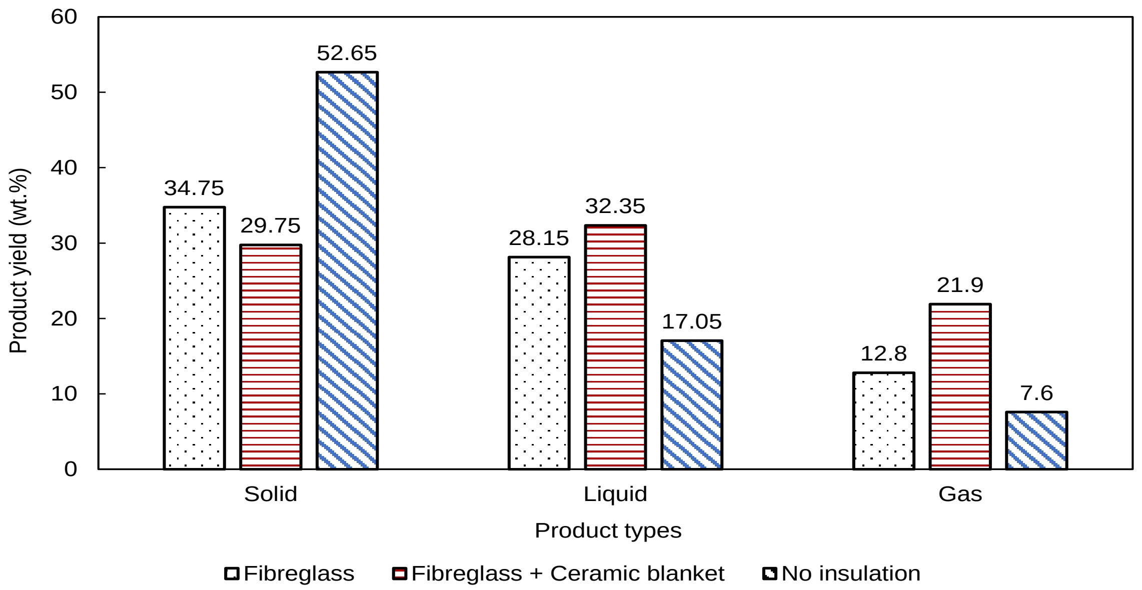

Figure 2: Product yield in different insulation methods

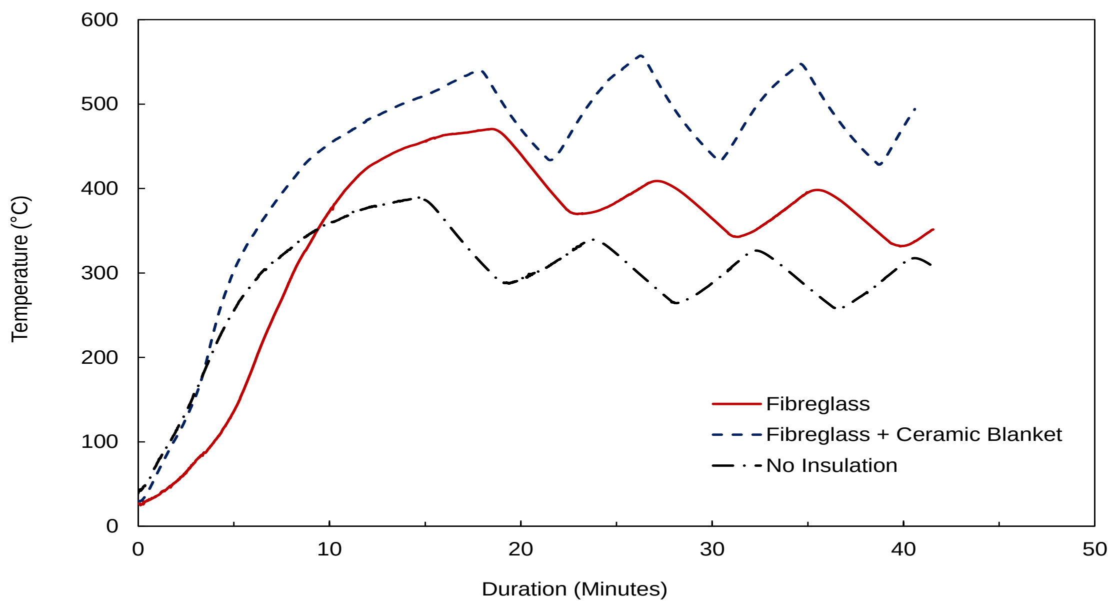

Figure 3: Temperature profile of Microwave Co-pyrolysis on Plastic and Sludge Waste with different insulation

A heat loss study was also conducted by analysing the temperature profile of each insulation method during the experiment as shown in Figure 3. The temperature profile of each insulation has displayed a similar trend, in which the temperature within the first 10 min increased progressively but fluctuated after 20 min of running. The fluctuation level of temperature in Setup 2 was the smoothest and most consistent compared to the other two insulations. This was because the low thermal conductivity of the ceramic blanket insulation layer prevented heat loss during the experiment as it significantly reduced the heat transfer out from the reactor wall, ensuring the temperature did not drop rapidly during idle conditions. In contrast, the temperature trend of Setup 1 and 3 slightly went into a downtrend during the temperature fluctuation period but Setup 1 performed better than Setup 3. Setup 1 maintained a higher temperature during the fluctuation period compared to Setup 3 due to the low thermal conductivity of fibreglass insulation creating a thermal barrier that prevents heat from escaping, maintaining the necessary high temperatures within the reactor. Furthermore, the highest temperature was obtained by Setup 2 at 557.19 °C, followed by Setup 1 (470.59 °C) and Setup 3 (391.11 °C). The maximum temperature resulting in Setup 2 could be attributed to the ceramic blanket insulation as it had better transparency to microwave and did not absorb microwave energy away from heating. For instance, the work of Ćurković et al. (2021) has agreed and revealed that the ceramic insulations are transparent to microwaves and they did not absorb any microwaves before being heated beyond a critical temperature (1260 °C) (Ritonga et al., 2021). Setup 2 also showcased the highest average temperature, 485.78 °C compared to Setup 1 (381.44 °C) and Setup 3 (305.09 °C). The average temperature is crucial to identify the pyrolysis rate during the experiment because a low average temperature can further lead to incomplete pyrolysis (Selvarajoo and Oochit, 2020). The temperature required for the feedstock to completely decompose might be higher than the average temperature achieved in this experiment, resulting in incomplete pyrolysis. It is observed from the work of Lopez-Urionabarrenechea et al. (2011), that the plastic feedstock required a higher temperature (500 °C) to pyrolyze and so only Setup 2 has met the temperature required. Based on the calculation, the highest heating rate has resulted in Setup 2 with 28.53 °C/min. Hence, a higher heating rate can promote a greater temperature level within the same period (Efika et al., 2018). The heating rates of Setup 1 and 3 were almost similar with a value of 23.83 °C/min and 23.94 °C/min. It can be claimed that fibreglass insulation (Setup 1) did not contribute much to increasing the heating rate during microwave heating as it will absorb microwave energy. Although the heating rate in each setup was higher than TGA used (20 °C/min), the solid yield obtained in each setup was still higher than the solid yield in TGA. It might be attributed to the average temperature in each setup being lower than 500 °C and the plastic feedstock could not be fully pyrolyzed so more solid residue was left over after the experiment. The highest heat loss among the three insulations was Setup 2 with 29 °C/min. It is because the maximum temperature obtained during Setup 2 was the highest among the insulation and so a larger temperature drop was expected from Setup 2, which in turn accelerated the rate of heat loss. The heat loss rates of Setup 1 and 3 were close to each other which was 23.21 °C/min and 20.81 °C/min due to similar heating rates and temperature gradients. At last, Setup 2 had the best performance in mass loss and heat loss rates.

4. Conclusions

The study evaluated the effectiveness of three different insulation setups in microwave pyrolysis by analyzing the mass loss and heat loss. Results indicated that Setup 2, which utilized a ceramic blanket and fibreglass, outperformed the other setups in several key areas. Setup 2 gave the lowest solid (biochar) yield of 29.75 wt.%, and the highest liquid (32.35 wt.%) and gas yields (21.9 wt.%). These results were attributed to the strong insulation effect of the ceramic blanket, which minimized heat loss and maintained a more consistent temperature throughout the process. The heat loss study further confirmed the superiority of Setup 2. The temperature profile for Setup 2 showed the least fluctuation with the highest peak temperature of 557.19 °C, as compared to Setup 1 and 3, which had a lower maximum temperature of 470.59 °C and 391.11 °C. Setup 2 maintained the highest average temperature of 485.78 °C, crucial for ensuring complete pyrolysis. Setup 3 had the highest solid yield (52.65 wt.%) due to its low heating rate and average temperature, causing incomplete pyrolysis. Setup 1 which uses only fibreglass, was less effective than Setup 2 but performed better than Setup 3. It had a moderate solid yield and lower average temperatures, indicating that fibreglass absorbs microwave energy, reducing heating efficiency. The findings demonstrate that the choice of insulation material significantly impacts the efficiency of the pyrolysis process. This suggests that ceramic insulation is highly suitable for applications requiring efficient thermal management and high-temperature stability as it proves superior in maintaining a higher and more consistent temperature while minimizing heat loss.

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