Effect of microwave susceptor design on the heating profile of co-pyrolysis between empty fruit bunches and waste truck tire

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Abstract. The effect of microwave susceptor design on the heating profiles of co-pyrolysis between waste truck tyre and empty fruit bunch was studied. Carbonaceous susceptor was used to elevate the pyrolysis temperature along with increased heating rate. Different design of microwave susceptor and its effect towards the heating profiles of the studied co-pyrolysis process was examined. The aim is to determine the effect of heating rates on the pyrolytic-oil yield, calorific value and energy recovery. From the study, it was revealed that the microwave susceptor design (D1) with a horizontal-layer single-bed, located at the bottom (SB-HL-B) of the feedstocks, showed higher heating rate (83 ^{o}C min^{-1}). Higher heating rates were observed to significantly increase pyrolytic-oil (39.0 wt%) and energy yield (59.0%). Such heating rate also upgraded the pyrolytic-oil properties, producing oil with higher calorific value (42.20 MJkg^{-1}). Thus, the present study demonstrated a viable method to optimise pyrolytic-oil yield in producing diesel-like fuel through the adoption of a microwave-assisted heating method.

1. Introduction

Microwave heating pyrolysis is considered to be one of the promising routes for waste feedstock recycling into renewable fuel and value-added materials [1-3]. The use of microwave heating is reported to provide various advantages with respect to rapid heating, volumetric heating, selective heating and short processing time compared to conventional heating [4-8]. Numerous studies have been published on the efficiency of microwave heating pyrolysis using different materials [4-7]. However, less emphasis was put on the microwave susceptor design. One of the notable studies on this aspect is from Antunes et al. [7]. They studied on the role of dielectric properties of susceptor on the biochar properties. The study investigated the effect of four different types microwave susceptors, namely biochar, charcoal, activated carbon and glycerol, towards biochar properties via microwave-induced pyrolysis of sewage. It was reported that activated carbon favors the microwave heating process, leading to increased heating surface area, which resulted in the biochar produced highest energy yield and carbon stability [7]. Hence, the microwave susceptor can be considered to be an important parameter, which will affect the pyrolysis process because the susceptors act as a source of internal heating for poor absorbent microwave energy materials, such as biomass. Microwave susceptor will transform the microwave energy into heat and transfers it to the target material through conventional heating conduction mode. Moreover, the presence of susceptor in a pyrolysis bed has also been shown to significantly improve the heating as well as rapidly increase reaction temperature and homogenous heating transfer. As a result of this, pyrolytic-oil yield is expected to increase along with possible beneficial oil quality improvements [5-8].

In a separate study, Idris et al. investigated microwave-assisted co-pyrolysis of waste truck-tyre (TT) and empty fruit bunch (EFB) using response surface methodology [8]. It was reported that microwave susceptor-to-feedstock ratio significantly affects chemical composition and product fraction of the liquid-oil. In this study, low microwave susceptor ratio of 33.0% had been observed to produce the highest olefin hydrocarbon mainly from D-limonene compound, while higher microwave susceptor ratio of 100% significantly increased the polyaromatic hydrocarbon (PAH) [8]. Many studies have also been reported in literature on the effect of different types of microwave susceptors, mass of feedstock-to-susceptor ratio along with the nature of carrier gas towards pyrolytic-oil yield and quality [6-7,9]. However, to the best of authors' knowledge, the study on different microwave susceptor design has yet to be investigated. Thus, for the present study, the effect of carbonaceous susceptor design on the heating rates as well as the pyrolytic-oil and energy yield was investigated. Activated carbon (AC) was used as a microwave susceptor due to its high microwave adsorption capacity for better heat transmission to the surrounding of feedstock [5,7]. Furthermore, from an economical point of view, AC is also cheaper as compared to other microwave susceptors, significantly reducing the operating cost. The outcome of the study was then used to optimise the heating characteristics with respect to product distribution, chemicals composition as well as the higher heating value (HHV) of the produced pyrolytic-oil.

2. Experimental

2.1. Materials

The Eco Power Synergy Sdn Bhd was supplied the granular steel wire-free of TT and FGV Palm Oil Mill was supplied the EFB biomass. The coconut activated carbon was used as a susceptor and all the materials were preheated at 120 °C in the circulation air oven for overnight to remove excess moisture.

2.2. Co-pyrolysis

The co-pyrolysis experiment is conducted with 2450 MHz and 1000 W microwave power. Further details of the experiment can be found in the study of Idris et al. [8]. The co-pyrolysis reaction parameters were fixed at 500 °C reaction temperature, 65:35 of EFB to TT ratio and 60 g of microwave susceptors. Five different types of microwave susceptor designs were examined as shown in Fig. 1. From the figure, microwave susceptor D1 (SB-HL-B) is depicted to consist of a single-bed with horizontal-layer and located at the bottom of feedstock. Design D2 (SB-HL-T) consisted also of a single-bed susceptor with horizontal-layer but located at the top of feedstock. Both had a similar dimension with approximately 20 mm thickness and 90 mm diameter. The designs of D3 and D4 consisted of rod-type susceptor. The fine-powdered activated carbon was compressed to have approximately 52 mm diameter and height 60 mm for D3 (SR-C). The design D3 consisted of a single-rod and located at the centre of reactor. Design D4 (SB-B-2R-C), on the other hand, consisted of a thin-layer of susceptor bed with approximately 90 mm diameter and 10 mm thickness. The design had 2 thin rod-type of susceptor with approximately 28 mm diameter and 50 mm height, which was located at the centre of reactor vessel. Besides this, design D5 was a small granular of microwave susceptor with approximately 3 to 5 cm, mixed homogenously with the feedstock. The ultimate, proximate analysis, calorific value and dielectric properties of materials (EFB, TT and activated carbon) were discussed in Idris et al. [8]. In the present study, the microwave power and reactor temperature has been calibrated according to the standard method has been discussed in reference [4]. Pyrolytic-oil (PO), char, non-condensable gas and energy (E) yields were calculated based on Eq. (1-4) as below:

$$Y_{PO}\ (\text{wt\%}) = \frac{M_{PO}\ (\text{g})}{M_O\ (\text{g})}\ \text{x}\ 100\% \tag{1}$$

$$Y_{Char}(\text{wt\%}) = \frac{M_{Char}\ (\text{g})}{M_O\ (\text{g})}\ \text{x}\ 100\% \tag{2}$$

$$Y_{Gas}\ (\text{wt\%}) = 100 - [\,Y_{PO} + Y_{Char}] \tag{3}$$

$$Y_E\ (\%) = Y_{PO}\ \text{x}\ \frac{\text{HHV of } PO\ (\text{MJ/kg})}{\text{HHV Mix Feedstock (MJ/kg)}}\ \text{x}\ 100\% \tag{4}$$

where M_{PO} is the mass of pyrolytic-oil (g), M_{char} is the mass of bio-char (g) and Mo is the initial mass of mixture feedstocks. To reduce the experimental error analysis, all the experiments have been repeated three times.

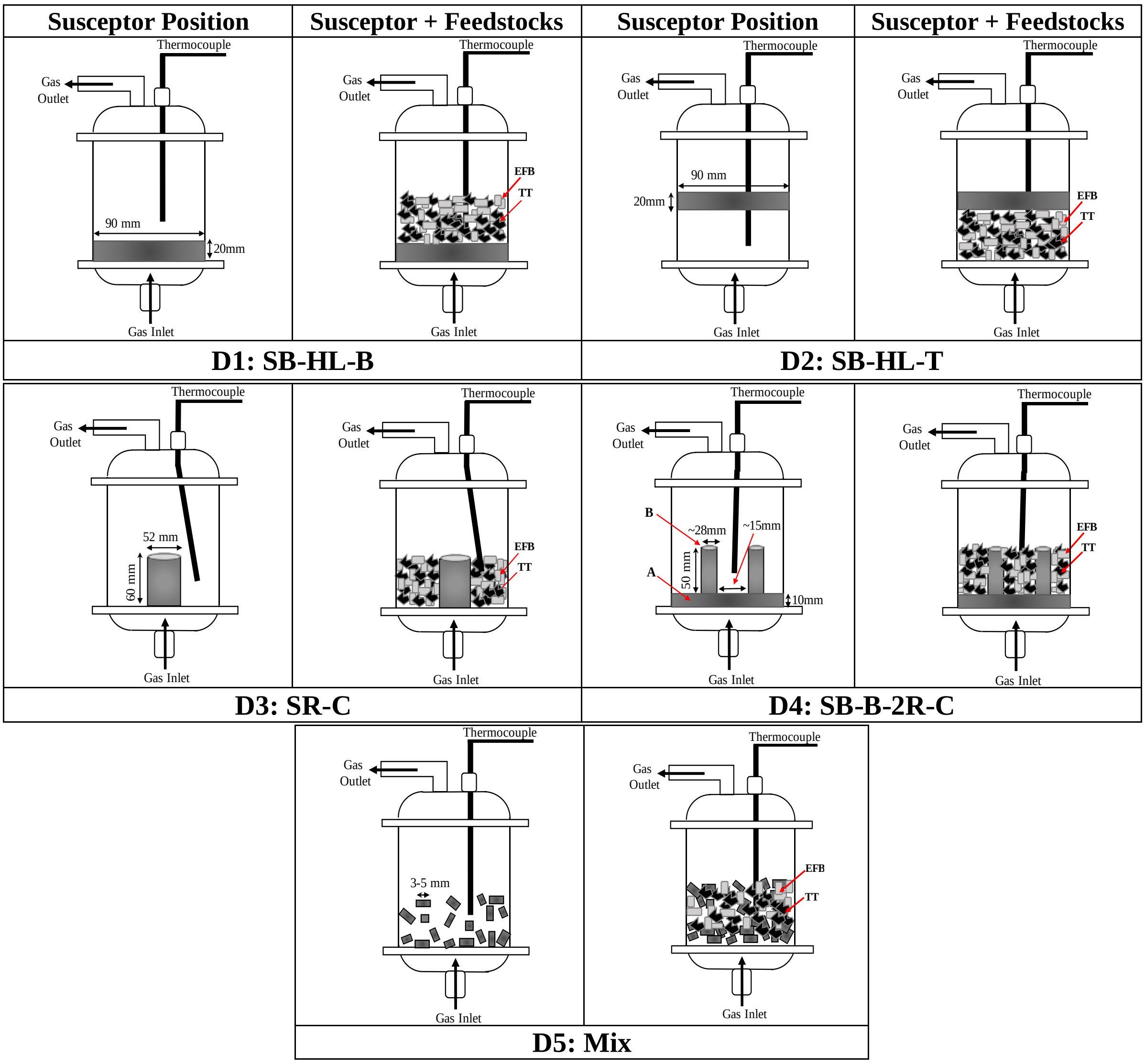

Fig. 1. Five microwave susceptor design (D1 to D5) with different dimension and position to optimised the co-pyrolysis of EFB/TT.

3. Results and Discussions

a. Effect of microwave susceptors design on the heating profiles

Figure 2 showed the effect of microwave susceptor design on the heating profiles of co-pyrolysis EFB/TT, using microwave-assisted pyrolyzer. In general, the heating profiles of co-pyrolysis EFB/TT at different microwave susceptor designs showed a similar trend. Both designs (D1 to D5) reached a plateau at the set target temperature of 500 °C in approximately less than 10 mins (Fig 2a). However, different susceptor designs exhibited different homogenous heating profiles. From the Fig. 1, it is shown that the carbonaceous susceptor designs with indirect exposure to the microwave radiation (D1, D3, D4 and D5) generated homogenous heating rates (Fig 2a). Less hotspots were observed from the heating profiles. It is important that the susceptor design to be homogenous with feedstock mixture in the reactor for uniform microwave field action in order to avoid formation of hotspots or micro plasma. A hotspot is a thermal instability, which occurs due to the non-linear dependence of the electromagnetic and thermal properties of the material, causing non-uniform process pyrolysis heating [9-10]. Non-uniform process heating could lead to the deterioration of pyrolysis reaction mechanism, which then influences the product distribution, chemicals composition as well as the higher heating value (HHV) of the pyrolytic-oil. Thus, uniform heating transfer of susceptor to feedstock is expected to lead to increased heating rate as well as shortening of the reaction time (approximately less then 5 mins to reach the reaction temperature) (see Fig 2b).

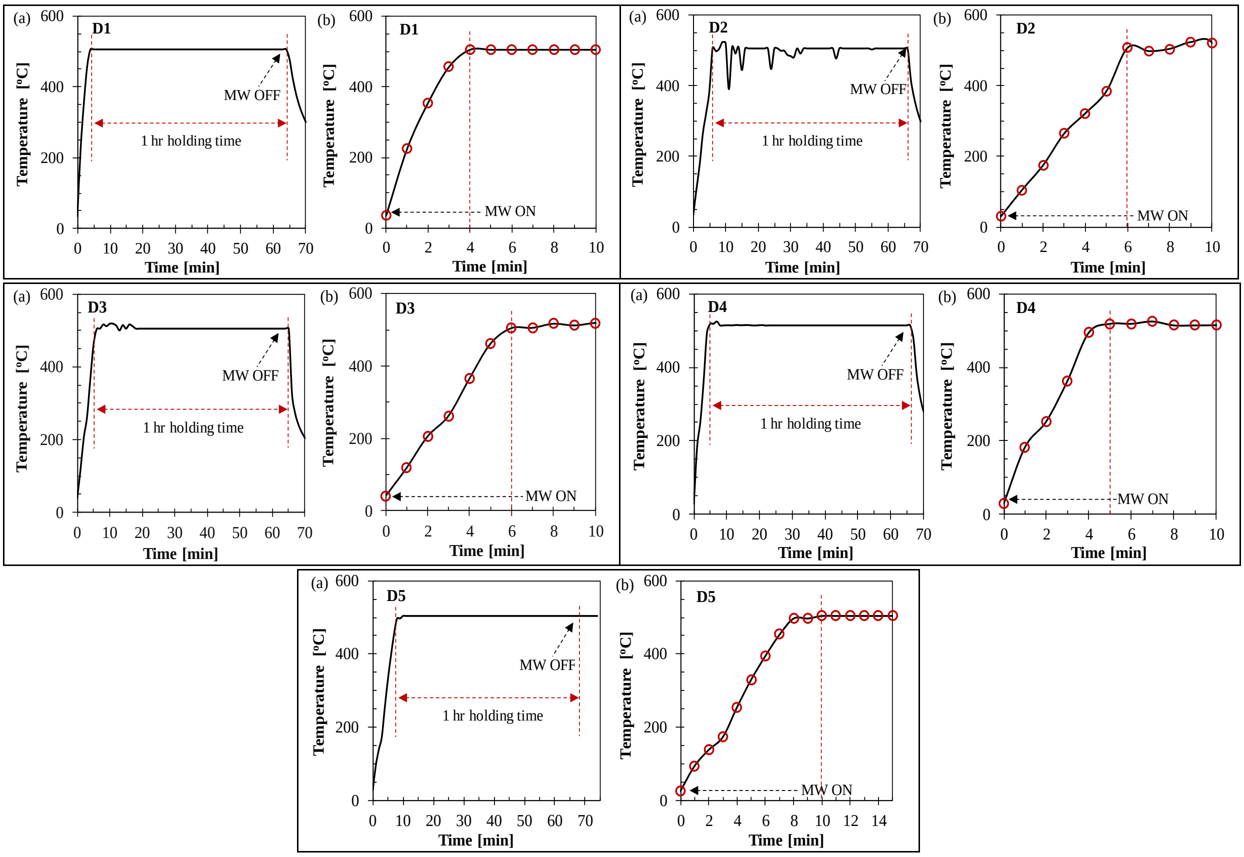

Fig. 2. Effect of microwave susceptor design (D1 to D5) on the heating profiles of co-pyrolysis EFB/TT (a) and the duration time to achieve a target temperature of 500 °C (b).

In contrast, design D5, consisting of the small granular susceptor and mixture homogenously with feedstock, achieved a longer reaction time with approximately 8 to 10 mins to reach the target temperature. This might be due to the non-fixed location of the susceptor distribution, which resulted in undesirable microwave wavelength. Conversely, design D2 directly was directly exposed to the microwave radiation, leading to uncontrolled heating. This is because of the in-heterogeneity of the microwave field, resulting in the formation of microplasma (see Fig 2). From the heating profile, it can be observed that large loops of temperature drop occurred, which indicated microplasma formation during the initial stages of the process. The observation is aligned with observations reported in literature, where microplasma formation is deemed to affect the heating rate of pyrolysis process [9-10].

The effect of microwave susceptor designs on the heating rate are given in Fig 3. From the figure, it was revealed that designs D1 and D4 have higher heating rate at approximately 73.55 °C and 67.68 °C min^{-1}, respectively. This could be due to the susceptor designs of D1 and D4 being able to provide a more homogenous heating transfer to the feedstock. During the microwave energy absorption, the susceptor particles selectively heat the surrounding of the feedstocks, which then subsequently transfers a bulk of heat by conduction to the adjoining feedstock particles. Such heat could be trapped between the susceptor and the feedstocks, promoting faster heating rates. Moreover, the flow of inert gas from the bottom of the reactor helped to carry the heat from the susceptor (bottom) towards the feedstock, inflating the feedstock combustion. Thus, it can be predicted that the liquid oil yield produced by designs D1 and D4 could be higher as compared to others. In contrast, designs D5 and D2, possessing non-uniform heating distribution and formation of micro plasma spots, resulted in lower heating rates with approximately 50.62 °C and 54.85 °C min^{-1} (see Fig 3). Therefore, a reduced pyrolytic-oil yield and quality are expected. On the other hand, the D3, consisting of single rod-type susceptor located at the center of the reactor vessel, has been observed to generate moderate heating rate of 58.72 °C min^{-1}.

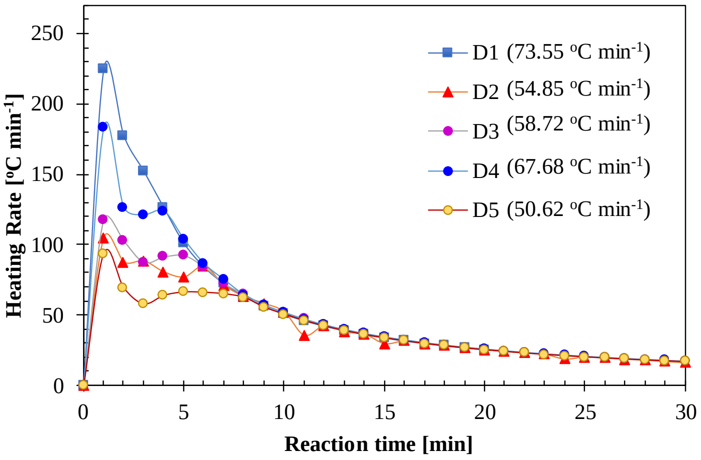

Fig. 3. Effect of microwave susceptor design (D1 to D5) on the heating rates of co-pyrolysis EFB/TT.

b. Effect of heating rates on the heating value of pyrolytic-oil

The effect of heating rates on the products distribution, higher heating value (HHV) and energy yields of the pyrolytic-oil was also investigated in Fig 4. In general, higher heating rate has been observed to lead to a significantly increased the pyrolytic-oil yield as well as the percentages of energy recovery. From the Fig.4a, it is shown that design D1 produces higher pyrolytic-oil yield (38.74 wt%), which is then followed by design D4 (38.16 wt%). As the heating rate decreased from 73.55 °C min^{-1} (D1) to 58.72 (D3), 54.85 (D2) and 50.62 (D5), the pyrolytic-oil yield decreased to 35.21 wt% (D2), 34.93 wt% (D3) and 34.20 wt% (D5), respectively. This is believed to be as a result of the lower heating rates, which increases the residence times of volatile vapour. Subsequently, this leads to secondary cracking, further increasing the non-condensable gas yield. Such trend can be confirmed from the non-condensable gas yield pattern. Likewise, higher heating rates have also significantly decreased the char yield due to the increased heating rate that rapidly increases the hot zone of the reactor to produce volatile vapor.

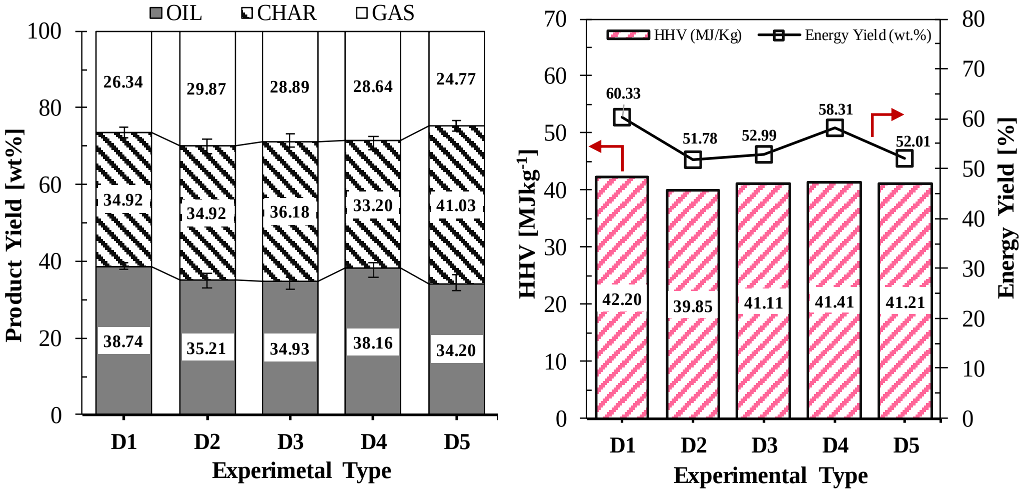

Fig. 4. Effect of heating rates on the products (a), higher heating value and energy yield of pyrolytic-oil (D1 to D5) produced from different design (b).

The product distribution is shown to be in correlation with heating rate as being illustrated in Fig 5. From the figure, it was revealed that the heating rate increased the liquid-oil while the non-condensable gas decreased, giving a positive impact on product yield with a coefficient of determination (R^2) of approximately 0.9667 (pyrolytic- oil) and 0.8874 (non-condensable gas), respectively. However, the char yield showed a negative impact on the increasing of heating rate, giving coefficient of determination (R^2) with approximately 0.9673.

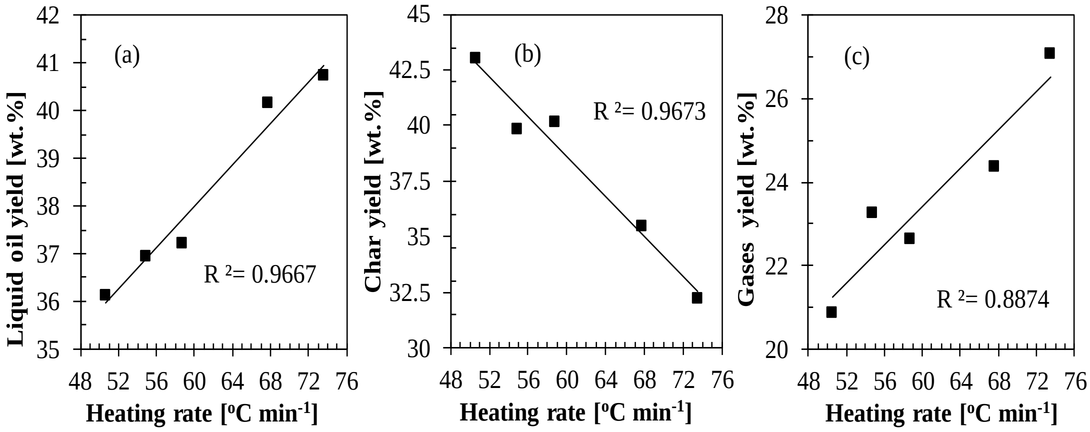

Fig. 5. Relationship between heating rates and yield of (a) pyrolytic- oil, (b) char and (c) non-condensable gases of co-pyrolysis EFB/TT at different susceptor design (D1 to D5).

The heating rate also significantly affects the calorific value as well as the energy yield of pyrolytic-oil (Fig 4b). From the figure, it is shown that higher heating rates from D1 and D4 produced pyrolytic-oil with highest heating value (HHV) of approximately 42.20 (D1) and 41.11 $MJKg^{-1}$ (D4), respectively. On the contrary, design D2 showed a lowest HHV of pyrolytic-oil of 39.85 $MJKg^{-1}$. This might be because of the microplasma formation during the pyrolysis process, which affected the uniformity of process temperature. Thus, this affected the pyrolytic-oil properties. Interestingly, the calorific value of the pyrolytic-oil produced using designs D3 and D4 remained higher, with an average value of 41.1 and 41.41 $MJkg^{-1}$, respectively. This is believed to be as a result of the indirect exposure of the susceptor design to the microwave that led to the production of less microplasma during the pyrolysis process. Therefore, it can be concluded that design D1 is capable of producing pyrolitic-oil with higher heating value and higher energy yield with approximately 60.33%, followed by design D4 with an amount 58.31%. Design D2 has been demonstrated to produce pyrolytic-oil with the lowest energy yield (51.78%) and lowest calorific value due to the non-uniform heating transfer.

4. Conclusion

The present study demonstrated that the microwave susceptor design influences the heating rate of co-pyrolysis process between truck tyre and empty fruit bunches. The susceptor design with homogenous mixing with the feedstock enhances the uniformity of heat transfer. Thus, this resulted in increased heating rates. Higher heating rates are also shown to enhance the pyrolytic-oil yield and upgrading of the oil properties as well as increased energy recovery. It was found that design D1 is capable of achieving higher heating rates (73.55 °C min^{-1}) and higher pyrolytic-oil (38.74 wt%) along with energy yield 60.33%). Therefore, design D1 has been shown to have greater potential to be adopted for optimisation of the microwave-assisted co-pyrolysis process between empty fruit bunches and waste truck tyre. This is expected to be capable of improving the heating characteristics of the product distribution, chemical composition as well as the calorific value of the pyrolytic-oil.

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