Research Article

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Integration of microwave co-torrefaction with helical lift for pellet fuel production

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Abstract: The heating performance of empty fruit bunch pellets (EFBPs) has been limited by its low energy density, high moisture, and ash content. Hence, microwave co-torrefaction (MCT) was performed with microwave heating unto waste oil mixed EFBP to produce high-energy biofuel. However, the non-homogeneous electromagnetic fields distribution in the microwave cavity results in an uneven heating behavior, producing the hot and cold spots. Hence, MCT coupled with helical lift was examined for its potential to improve heat distribution. The effect of temperature and types of waste oil on the proximate analysis and surface properties were studied. In comparison to the conventional torrefaction using a furnace (>30 min), MCT provided rapid heating (50–80°C min⁻¹) and a shorter process time (10 min). The use of helical lift with 2-dimensional movement – rotational (24 rpm-min⁻¹) and vertical motion (5 cm-min⁻¹) simultaneously, distributed microwave radiation uniformly for rapid heating. The proximate analysis demonstrated that the ash content was reduced from 8 to 3 wt%, and the highest fuel ratio of 2.0 was achieved. Additionally, the highly porous structure of EFBP biochar can act as an activated carbon precursor. MCT coupled with helical lift represents a promising approach to prevent hot spots during microwave heating.

Keywords: microwave, torrefaction, empty fruit bunch, helical lift, hot spot

1 Introduction

Torrefaction is a thermal pre-treatment method under an inert environment, typically used to enhance biomass value as co-firing materials, focusing on the biochar yield and energy generation at a lower temperature of 200–300°C for several minutes or hours. Microwave heating could be integrated with the torrefaction process to improve the overall process efficiency and product quality [1]. However, there is lacking detailed understanding of the mechanism of microwave heating during torrefaction. Hence, a significant attribute of thermochemical processing of biomass in microwave co-torrefaction (MCT) system is essential to improve the storage period and energy value of torrefied product [2,3]. Microwave heating has demonstrated several advantages in terms of volumetric and dielectric heating by electromagnetic radiation in bulk conditions.

MCT is a relatively new and unexplored research, especially from the standpoint of microwave heating and reactor design that involve higher temperatures of heating. Most of the literature was focused on the conventional heating of torrefaction whereas research for microwave heating in torrefaction is limited [4]. The studies of torrefaction using conventional heating were usually performed under several process parameters such as time, temperature, and constituents of feedstock, while the microwave power and irradiation time were process variables reported in MCT in the existing studies [2,5–7]. However, torrefaction temperature distribution and weight reduction compensation methods are rarely reported in the literature [8].

Several challenges have been found in MCT related to the uneven temperatures that occurred (Figure 1a) and overheating at the edge due to the non-uniform distribution in the electromagnetic field that needs to be overcome to fully utilize microwave heating in torrefaction.
The existing studies on the distribution of microwave heating in the reactor were reported on the size, shape, surface condition of the cavity [9], multi-combination of magnetron [10], magnetron operating frequency [11], frequency distribution [12], and incorporation of mode stirrer and rotational table [13–15] to improve the uniformity of microwave heating. The variation in dielectric and proximate properties of the material with the temperature changes [16,17], load geometry [18], and sample location inside the microwave cavity could also be the significant parameters to affect the electromagnetic fields distribution and microwave heating behavior. The electromagnetic field distribution is critical for controlling microwave heating uniformity via the installation of a helical lift to investigate the effects of microwave heating temperature and the blending of waste oils.

2 Material and methods

2.1 Materials preparation

Empty fruit bunch pellets (EFBPs) were collected from a palm oil mill in Sarawak, Malaysia. The pellets with a diameter of 8 mm and length of 5–20 mm were air-dried (DEFBP) before being subjected into MCT. The samples were shredded into powder and sieved for further analyses. Used cooking oil (UCO) from fast food restaurant in Sibu, Sarawak, Malaysia, was filtered and stored in a dark sealed bottle before mixing with EFBP.

2.2 Experimental setup of MCT

As shown in Figure 2, the schematic diagram of the MCT consists of eight major components: (i) magnetron with a fixed power of 1,000 W, (ii) microwave cavity (110 mm × 110 mm × 110 mm), (iii) 250 mL quartz reactor, (iv) waveguide, (v) type K thermocouple, (vi) multi-range temperature controller, (vii) helical lift, and (viii) a borosilicate condenser set. A flat quartz glass was employed to isolate the waveguide from the microwave cavity. The helical lift was tuned to run at 24 rpm with 5 cm·min⁻¹ vertical movement to achieve an even microwave radiation to the EFBP.

Figure 1: Empty fruit bunch pellet: (a) after heating in static condition and (b) after even heating in 2D motion.
The temperature of torrefaction was set using a temperature controller and recorded via a thermocouple. The helical lift was used to enable rotational and translational motion to work simultaneously to improve microwave heating distribution. The MCT was conducted under a self-purging inert atmosphere (limited oxygen), in which no nitrogen gas purging was required. Hence, it is more economically feasible compared with the conventional torrefaction process that requires continuous purging of nitrogen gas. 50 g of EFBP was added to the quartz reactor and then heated to a temperature range of 200–250°C and 250–300°C for 30 s. EFBP was then mixed with UCO before being subjected to a torrefaction procedure. The temperature profile of torrefaction experiments (raw EFBP, DEFBP, and EFBP/UCO) was studied by recording the temperature. The torrefied pellets were cooled and stored in a desiccator for further analysis.

2.3 Characterization of torrefied products

The proximate analysis was conducted referring to ASTM D 5142-02a with an electric furnace and analytical balance. The fuel ratio of the torrefied product was then calculated by dividing fixed carbon over volatile matter. The surface morphology of raw and torrefied pellets was examined using a JOEL-6000 scanning electron microscope (SEM) which operates at an accelerating voltage of 15 kV. The oxygen bomb calorimeter (LECO, AC-350) was used to calculate the calorific value of the sample according to ASTM D5865 [21].

3 Results and discussion

3.1 Temperature profile of microwave co-torrefaction

Figure 3 compares the temperature profile of microwave torrefaction (MT) and MCT. The process of microwave heating can be divided into three stages: (1) drying stage to remove moisture content, (2) further heating stage, and (3) torrefaction stage. The temperature profile was taken from the initial EFBP temperature (25°C) until the maximum torrefaction temperature of 300°C.

MT of EFBP shows high heating rate of 80°C·min⁻¹ till 100°C in the first 60 s and then reduced to 10°C·min⁻¹ from 100°C to 250°C as the biomass has low microwave absorption efficiency after all moisture has been released but increased to 50°C·min⁻¹ from 250°C to 300°C. While
MCT also shows a relatively low heating rate of 30°C min\(^{-1}\) to reach 100°C, further achieved to 150°C with 12°C min\(^{-1}\) heating rate, and shows a higher heating rate of 80°C min\(^{-1}\) from 150°C to 300°C.

The high heating rate observed at the beginning of both MT and MCT could be attributed to the microwave heating of water in the form of moisture, where water is generally known as a strong microwave absorbent \(\text{[22]}\).

Previous studies \(\text{[5,6]}\) also exhibited a similar trend in the temperature profile of samples, especially on a small plateau region around 100°C which corresponded to the time spent in the removal of moisture from the biomass.

MT shows a lower heating rate between 100°C and 250°C was contributed by the relatively low dielectric constant and the loss factor of EFBP \(\text{[22]}\). Then, the heating rate was increased to 50°C min\(^{-1}\) from 250°C to 300°C due to the exothermic torrefaction stage and changes in biomass to carbon structure \(\text{[23,24]}\). However, the additional UCO in MCT has reduced the de-volatilization temperature to cause a rapid increase in the heating rate (80°C min\(^{-1}\)) at about 150°C \(\text{[25,26]}\).

### 3.2 Characterization of raw EFBP and torrefied products

#### 3.2.1 Proximate analysis, fuel ratio, and higher heating value

Table 1 shows the proximate analysis of raw EFBP and torrefied EFBP. Raw EFBP showed a high content of moisture (15 wt%) that caused the fungus to spread among the EFBP during the storage period. High volatile matter (62 wt%), ash content (8 wt%), and low fixed carbon content (15 wt%) correspond to the lower heating value of EFBP, which also lead to severe fouling, slugging, and ash meltdown during combustion \(\text{[27]}\).

As the temperature increased from 200°C to 250°C, the volatile matter of torrefied EFBP from MT and MCT decreased progressively to 52 and 49 wt%, respectively, whereas the fixed carbon increased to 36 and 44 wt%, respectively. This trend was predicted as the increase in temperature promoted the partial decomposition of the lignocellulose and the removal of volatile matter enriched the fixed carbon \(\text{[28]}\). However, MCT shows a significant increase of fixed carbon to 63 wt% and reduces the ash content to 3 wt% at a temperature range of 250–300°C when compared with MT. This indicates that the addition of waste oil increases the de-volatilization rate and also enhances the collapsing of organic materials to produce fixed carbon. Hence, the hydrocarbon chain of waste oil supplies the additive energy \(\text{[29–31]}\) to the EFBP to compensate for the weight loss and increase the heating energy of EFBP as a solid fuel for the boiler.

The fuel ratio of the MCT increased with the torrefaction temperature in line with the increase in fixed carbon and the decrease in a volatile matter of the torrefied products. As the temperature increased from 200 to 250°C, the fuel ratio of torrefied EFBP from MT and MCT

| Temperature   | Raw EFBP | Microwave torrefaction | Microwave co-torrefaction |
|---------------|----------|------------------------|---------------------------|
| Moisture content (wt%) | 15       | 4                      | 1                         | 2                      |
| Volatile matter (wt%)    | 62       | 52                     | 33                        | 49                     |
| \(^a\)Fixed carbon (wt%) | 15       | 36                     | 58                        | 44                     |
| Ash (wt%)              | 8        | 8                      | 8                         | 5                      |
| \(^b\)Fuel ratio | 0.2      | 0.7                    | 1.8                       | 0.9                    |
| Calorific value (mJ kg\(^{-1}\)) | 17       | 19                     | 22                        | 23                     |

\(^a\)Fixed carbon = 100 wt% – moisture – volatile matter – ash.
\(^b\)Fuel ratio = fixed carbon/volatile matter.
increased to 0.7 and 0.9, respectively. MT and MCT obtained the highest fuel ratio of 1.8 and 1.9, respectively, at 300°C. The enhancement in fuel characteristics was further monitored through the calorific value recorded. MT and MCT torrefied EFBP achieved the highest calorific value of 22 and 25 mJ·kg⁻¹ at 250–300°C, respectively. Thus, the addition of the UCO coupled with the increase in torrefaction temperature was found to significantly improve the fuel characteristics of the torrefied products through the contribution of higher fixed carbon content.

3.2.2 Surface morphology

The surface texture of the raw EFBP was rough, uneven, and undulating as shown in Figure 4. The disorder of cross-section shown in Figure 4a might be resulted from the cutting effect during sample preparation. Besides that, Figure 4b shows that the EFBP surface was covered with lump structures that could be attributed to silica [32]. Figure 4c shows the magnified EFBP surface at 1,000 times, and it can be observed that the silica is present as sphere objects within the surface of EFBP.

Figure 5 shows the comparison of the surface texture of MCT of EFBP at 200–250°C and 250–300°C, and with or without waste oil added. The SEM images of Figure 5a and b showed more opened pores with the presence of waste oil at a temperature of 200°C. As a result, more silica body was released thus creating more tiny rudimentary pores [33]. It has also been observed that the torrefied char obtained at a temperature of 300°C in Figure 5c showed a uniform honeycomb structure which
is normally reported [34,35]. Moreover, patches of crack and cell wall breakdown have been observed in Figure 5d when waste oil is applied. However, higher temperatures (300°C) produced better-torrefied products via the decomposition of hemicellulose and cellulose of EFBP into carbon.

4 Conclusions

Microwave co-torrefaction (MCT) has shown a high energy-efficient approach in enhancing empty fruit bunch pellet (EFBP) into higher energy co-firing fuel. Integration of microwave and used cooking oil has torrefied the EFBP at a rapid volumetric heating rate up to 80°C min\(^{-1}\) and short torrefaction time (10 min). The helical lift also provides 2D motion with better microwave heat distribution. Torrefied EFBP by MCT at 250–300°C has produced high fixed carbon content (63 wt%), low volatile matter (33 wt%), and low ash content (3 wt%). The differences shown in the surface morphology of EFBP before and after MCT were attributed to the removal of the silica body. The results have proven that the utilization of MCT can generate an economically more viable and sustainable torrefaction process. Evidence of synergy between two heterogeneous feedstocks observed in temperature profiles may provide an insight into a more systematic approach to co-torrefaction. A reliable reaction kinetic data of mixing the heterogeneous feedstocks in different mass ratios can contribute to the designing and operation of industrial systems, promising improved overall process efficiency.

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