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Integrating microwave heating pre-treatment to improve torrefaction of food waste

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Abstract. The food waste (FW) disposal is one of the main issues of concern, as it affects environmental and sustainable development in Malaysia. FW should be utilized to produce more valuable products such as energy. However, FW is characterized by its low high heating value (HHV) and high moisture content and which lower the energy efficiency during energy production process. To overcome this problem, torrefaction assisted by microwave heating pre-treatment is used to upgrade FW properties to produce solid biofuel which is called as biochar. The objective of this study is to investigate the feasibility of microwave (MW) heating power at 240 W for 5 min to enhance the quality of torrefied FW. The pre-treated FW is then torrefied at three different temperatures (280, 300 and 320 °C) for 30, 45 and 60 min. The torrefied FW was then characterized in terms of ultimate and proximate analysis, HHV, mass and energy yield as well as its functional groups. The optimum condition of torrefaction in this study was 320°C and 30 min with HHV of 23.82 MJ/kg, 95.54% of energy yield and 84.28% of mass yield. This suggests that torrefied FW with MW heating pre-treatment has the potential to be used as an energy source.

1. Introduction

In 2019, 1.3 billion tons of FW generated every year globally. In Malaysia, it is estimated that 6.7 million tons of food waste (FW) will be generated a year in 2020 [1]. This tremendous amount of the FW is mainly being disposed of at landfill as it is relatively inexpensive and simple to apply. However, once the maximum capacity of the landfill site is reached, identifying suitable locations for new landfills is a serious issue. Moreover, disposing the FW at the landfill has creates various environmental problems such as groundwater contamination, greenhouse gas emissions which contribute to the climate change, unpleasant odour and leachate formation [2].

Conversion of FW into value-added products such as biofuel energy is becoming an interesting option to reduce the accumulating wastes at landfill as well as reducing the dependency in fossil-based fuels. The use of FW biomass as a new renewable energy sources is necessary to reach the energy demand in the world.

The utilization of FW as a renewable energy resource however is quite challenging for several reasons that are related to its high moisture content, lower higher heating value (HHV) and lower energy density [3-4]. These challenges may be overcome through torrefaction. Torrefaction is a thermal pretreatment that converts biomass into biochar at low operating temperature of 200-240 °C in an inert



condition [4]. It has been found to be effective in improving the energy density which provides a much better fuel quality for gasification and combustion applications [5].

During the torrefaction process, water content and volatile matter in the biomass are released and the biopolymers include cellulose, hemicellulose and lignin are partly decomposed, giving off various types of volatiles [6]. The final product is the remaining solid, dry and blackened material that is referred to as torrefied biomass or biochar.

Torrefaction has been conducted on variation of biomass including lignocellulosic wastes such as oil palm solid waste [7, 8], forest residues [5], coffee residues [9], all of which shows promising results. A limited amount of work done on food waste torrefaction as compared to the lignocellulosic wastes [6]. At the moment, Abdul Samad et al. [10] and Abdul Rasid et al. [11] are among those who studied torrefaction of FW in Malaysia.

The torrefaction of FW can be further improved by integrating microwave (MW) heating pre-treatment prior to the torrefaction process. MW heating has the potential to alter the structure by creating more pores and bigger surface which increase the efficiency of the torrefaction process.

The purpose of this study is to investigate the improvement of torrefied food waste properties by integrating MW heating as a pre-treatment. The MW heating pre-treatment will be carried at 160 and 240 W for 5 min. The pre-treated FW is then torrefied at three different temperatures (280, 300 and 320 °C) for 30, 45 and 60 min.

2. Methodology

2.1. Material

FW utilized in this study was collected from the Universiti Malaysia Pahang cafeteria which contained of bones (74.03%), rice (13.81%), vegetables (10.20%), and others (1.96%). The samples were dried overnight in the oven at 105 °C. The dried FW was ground and sieved to get uniform particles size ranging from 0.5 to 1 mm. The properties of raw FW samples used in this work are tabulated in table 1.

Table 1. Raw FW Properties

Raw FW Properties	
Moisture content (% , wet)	61.43
HHV (MJ/kg, dry)	21.01
Elemental (wt.%, dry):	
C	44.41
H	7.15
N	5.20
O	39.46
S	3.78

2.2. Experimental Procedure

2.2.1. Microwave heating pre-treatment. Microwave oven (SHARP, model: R207EK) is used for the microwave heating pre-treatment. A 20 g of dried FW is placed in the microwave oven and heated at 160 and 240 W for 5 min. After microwave heating, the FW is proceeded with torrefaction process.

2.2.2. Torrefaction process.

Figure 1 shows the schematic diagram of torrefaction set-up. The system is consisting of nitrogen tank, flow controller, reactor, temperature controller, furnace and liquid collection flask. A tubular reactor with diameter of 3.7 cm and length of 10 cm was used in for the torrefaction process. 20 g of the treated food waste is loaded in the reactor. The FW torrefaction process was carried out at 280°C, 300°C and

320 °C for 30, 45 and 60 min. The reactor was purged by nitrogen gas (N₂) with flowrate of 2 L/min for 10 min before start the torrefaction process. This purposed of this step is to create an inert environment. The nitrogen gas was flowed continuously with the same flow rate during the torrefaction. The solid product was collected once the reactor was cooled down. Experiments was repeated thrice under the same conditions to ensure reproducibility of the results. The samples were stored in desiccator in order to avoid moisture reabsorption.

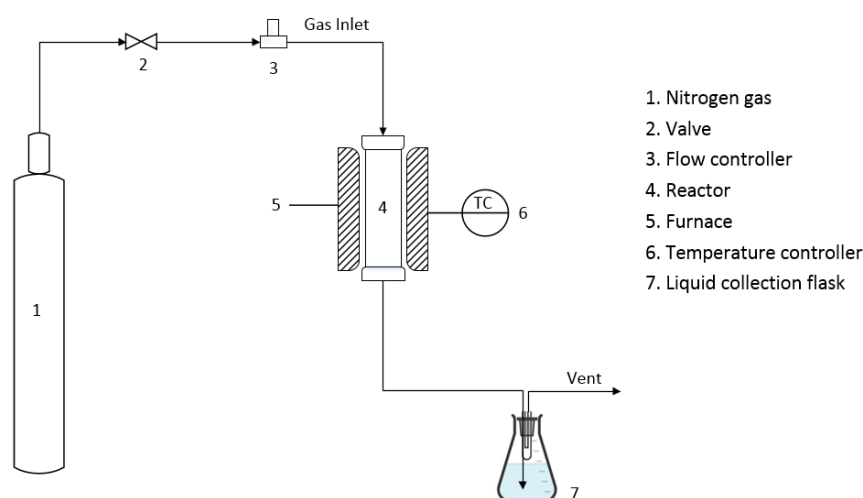


Figure 1. The diagram of torrefaction system.

2.3. Product analysis and characterization.

The proximate and ultimate analysis, high heating value (HHV), mass and energy yield, functional group and morphology analysis of the FW has been performed. The proximate analysis was conducted using TGA (Q500-0617). The samples were heated for 10 °C/min from 30 to 900 °C under the flow of 10 ml/min N₂. Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) is used for functional group and morphology analysis, respectively. For the HHV, the analysis is conducted using bomb calorimeter (model IKA Calorimeter C2000 Basic). The ultimate analysis is conducted using the CHNS analyzer to determine the C, H, N, O and S contents of the samples. ATR machine (Nicolet iS5 Thermo Scientific ID7) with OMNIC software is used for functional group analysis. The mass and energy yield are calculated using equation (1) and equation (2), respectively.

$$\text{Mass Yield (\%)} = \frac{M_t}{M_o} \times 100\% \quad (1)$$

Where,

M_o = the mass of sample before torrefaction (g)

M_t = the mass of sample after torrefaction (g)

$$\text{Energy Yield (\%)} = \frac{M_t \text{ HHV}_t}{M_o \text{ HHV}_o} \times 100\% \quad (2)$$

Where,

HHV_o = the lower high heating value (MJ/kg)

HHV_t = the high high heating value (MJ/kg)

3. Result and Discussion

3.1. Preliminary Study

Preliminary study on MW heating pre-treatment is conducted to find out the effect of MW on the structure of FW. Two different MW power were selected for the preliminary study which are 160 and 240 W for 5 min. The Higher Heating Value (HHV) of the torrefied FW (at 320 °C for 30 min) is 23.04 and 23.82 MJ/kg using MW power of 160 and 240 W respectively. This finding shows that, MW heating pre-treatment with 240 W is able to produce higher energy of biochar compared to 160 W.

The scanning electron microscope (SEM) images of the raw FW, with and without exposing to the MW heating are illustrated in Figure 2 and Figure 3. It can be seen that the surface of the raw sample without MW heating is more compact, dense and non-porous. In contrast, MW heating process was altered the structure by creating more pores which produced bigger surface area. MW heating has been reported to rupture cell walls caused by temperature and pressure increases due to the thermal effects of the MW [12].

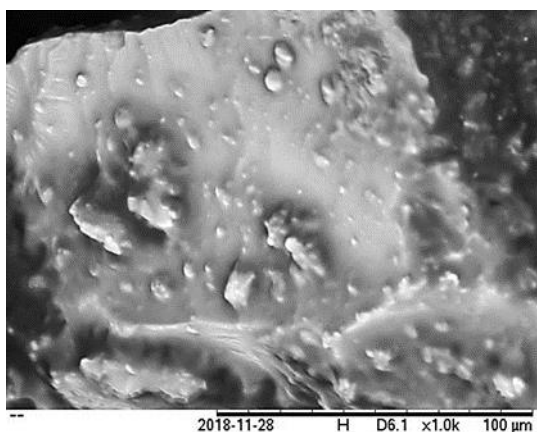


Figure 2. SEM image of raw sample without MW heating (Magnification x1000) .

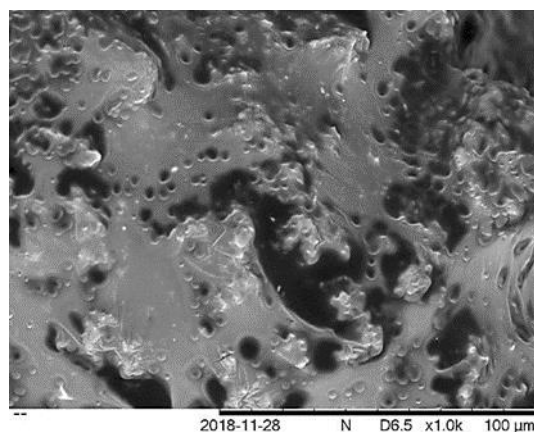


Figure 3. SEM image of raw sample with MW heating (Magnification x1000) .

3.2. Torrefaction Study

The torrefaction of FW is conducted after the optimum condition of MW heating pre-treatment has been selected in the preliminary study (240 W and 5 min). The torrefaction were performed at three different temperatures (280, 300 and 320 °C) for 30, 45 and 60 min. The analysis of the torrefied FW includes ultimate and proximate analysis, HHV, mass and energy yield.

3.2.1. Ultimate analysis. The ultimate analysis is conducted to determine the C, H, O, N and S compositions in the torrefied FW and the results is tabulated in table 2.

Table 2. Ultimate analysis of torrefied FW

Torrefaction conditions		Ultimate analysis (dry wt%)				
Time (min)	Temperature (°C)	C	H	O	N	S
30	280	46.85	6.72	39.81	6.33	0.29
	300	48.37	6.62	38.54	6.19	0.28
	320	53.02	6.49	33.72	6.51	0.26
45	280	50.38	8.82	32.29	6.45	2.06
	300	52.39	8.79	28.89	6.07	3.86
	320	55.50	7.10	28.06	5.83	3.51
60	280	51.85	8.55	30.45	6.36	2.79
	300	52.78	7.53	29.46	6.46	3.77
	320	54.93	7.34	28.38	5.80	3.55

An increase in torrefaction temperature and time resulted an increase in C and decrease in H and O of the biochar. The C content increased up to 55.50 from 44.41 % (in raw FW) while O is reduced from 39.46 to 28.06% after being torrefied. The increase of the C content is contributed by the loss of moisture and other volatile component which contained O and H such as O₂, CO, and CO₂ as explained by Poudel et al. [3], Rago et al. [4] and Abdul Samad et al. [10]. High content of C and low content of O is required in order to produce biochar with high HHV. The N elements only has changed slightly after torrefaction. The lowest element in the torrefied FW is S.

3.2.2. Proximate analysis. The proximate analysis of FW is conducted after being torrefied at 280, 300 and 320 °C for 45 min. The moisture content (MC), volatile matter (VM), ash content (AC) and fixed carbon (FC) is shown in table 3.

Table 3. Proximate analysis of torrefied FW.

Temperature (°C)	Composition (dry wt%)			
	MC	VM	AC	FC
280	2.51	56.27	29.11	12.11
300	2.23	50.17	33.23	14.37
320	1.87	43.87	34.44	19.82

It can be observed that torrefied FW contains more AC and FC but less VM and MC as the temperature increases. A similar trend was reported by and Rago et al. [4] and Samad et al. [10]. The VM of the biochar is reduced from 56.27 to 43.87 % when the temperature increase from 280 to 320 °C. This is due to the devolatilization during the torrefaction. The devolatilization is more intense as the temperature increased. This is also the reason why the FC of the biochar is increases from 12.11 to 19.82 % when the temperature increased.

Torrefaction technique could be used to convert raw FW with high moisture content (61.43 %) to a very low moist biochar (1.87 %). This value is lower than the moisture content of a coal [4]. The reduction of moisture content and the increase of FC as temperature increases will enhance the calorific value of the torrefied FW.

3.2.3. Higher Heating Value (HHV). HHV represent the energy contain in a biochar. The HHV of torrefied FW at different conditions are shown in Figure 4.

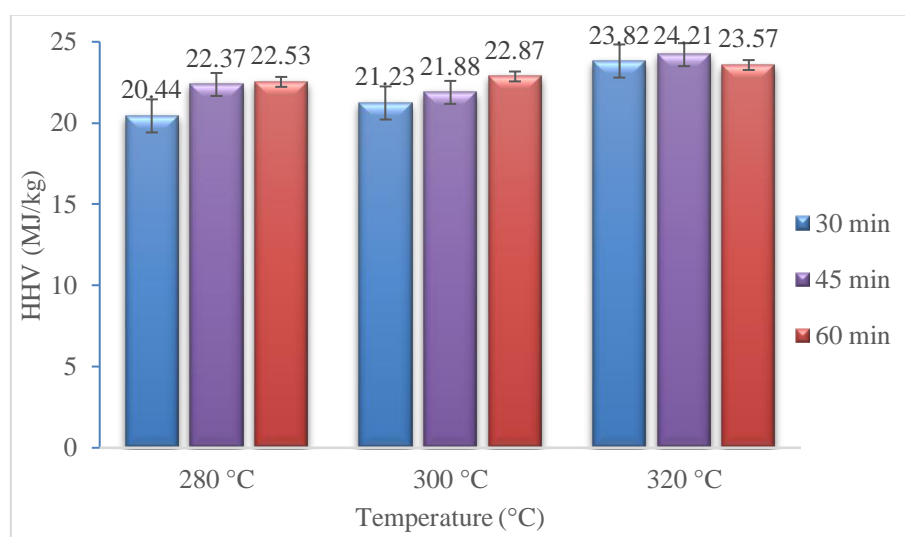


Figure 4. High heating value (HHV) of torrefied FW.

HHV is increases with torrefaction temperature and time accept at 320 °C, where the HHV is start to drop when the time increases from 45 to 60 min. The increased of HHV is due to the loss of moisture and the emission of volatile gaseous which is lead to increase the C content as discussed in the previous section. The increase the C content enhances the value of HHV. The highest HHV, 24.21 MJ/kg was obtained at 320 °C and 45 min.

3.2.4. FTIR Spectra. The functional group of the raw and torrefied FW was analyzed using FTIR as shown in Figure 5.

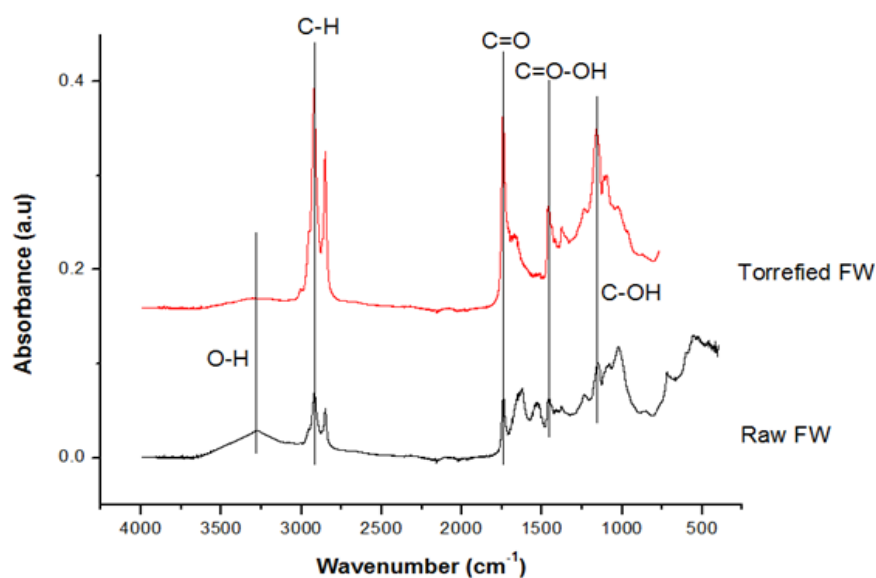


Figure 5. FTIR spectra of raw and torrefied FW.

All the carbon bond peaks are increased after torrefaction accept the O-H group. The intensity of O-H peak is reduced after torrefaction due to dehydration reactions or moisture lost. As the carbon bond contained higher energy compared to O-H bond, the high intensity of carbon bond in the torrefied FW improved the HHV of the FW [6].

3.2.5. Mass Yield. The mass yield of torrefied FW at various operating conditions are demonstrated in Figure 6. It is calculated based on equation (1)

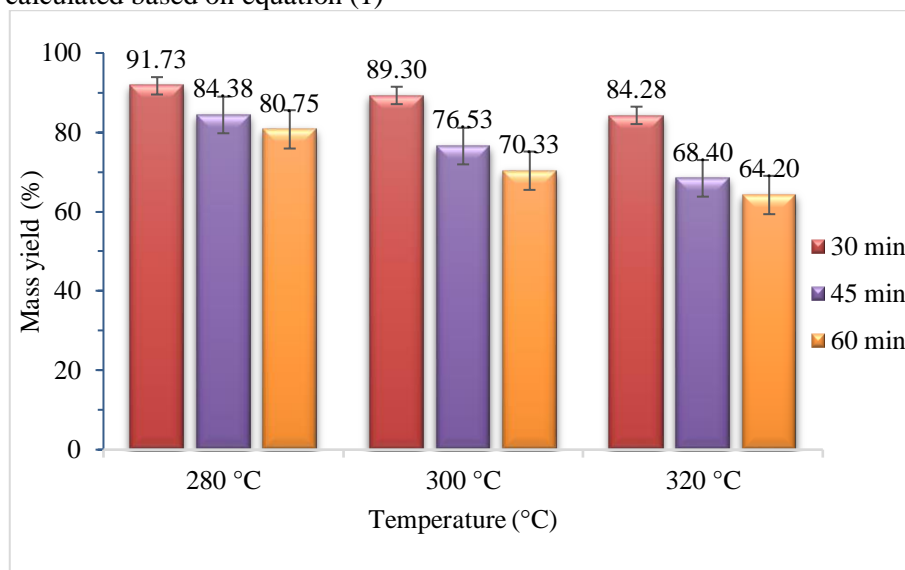


Figure 6. Mass yield of torrefied FW

As can be seen, the mass yield decreased progressively with temperature and time. The mass yield of torrefied FW is drastically decreased at higher temperature and the reduction become higher as the time increased from 30 to 60 min. For example, at 280 °C, the mass yield drop about 7.38% (from 91.73 to 80.75%) as the time increases from 30 to 45 min. However, the mass yield dropped to 12.77% and 15.88% at 300 and 320 °C respectively with the same duration. The mass yield of torrefied FW is the lowest (64.2%) at the most severe condition (320 °C and 60 min). At 280 °C, the reduction of mass yield contributed by moisture lost and some volatiles (O_2 , CO and CO_2) emission from the degradation of hemicellulose in the FW. At temperature more than 300 °C, heavier volatiles (methane, acetic acid, formic acid and aromatics) are released from the thermal degradation of cellulose, protein and hydrocarbon which cause more reduction of mass yield [6].

3.2.6. Energy Yield. Energy yield is a parameter which measure the balance between HHV enhancement and mass loss. It was determined using equation (2) and presented in figure 7. The figure shows that, an increase in temperature and time lowers the energy yield.

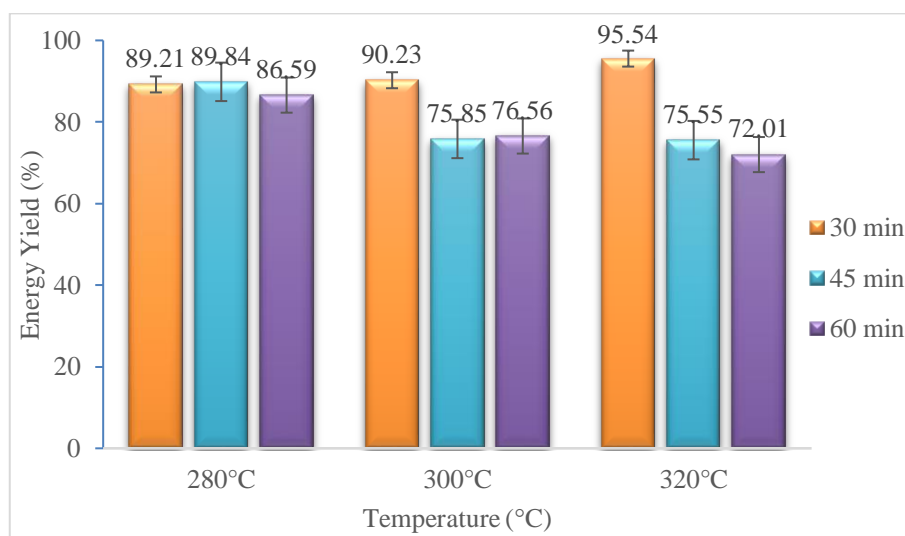


Figure 7. Energy yield for torrefaction process.

Based on the energy yield, temperature of 320 °C and torrefaction time of 30 min is the optimum condition for the torrefaction as it offers the highest energy yield (95.54%).

4. Conclusion

Microwave heating pretreatment increases the surface area of FW by creating pores which increases the thermal degradation during torrefaction. Torrefaction at 320 °C and 45 min produce biochar with highest HHV 24.21 MJ/kg. Even though, the torrefaction principally aims to produce highest HHV, however severe mass loss should be avoided. Therefore, the optimum condition of torrefaction in this study was 320°C and 30 min with HHV of 23.82 MJ/kg, 95.54% of energy yield and 84.28% of mass yield. It can be concluded that torrefied FW pretreated with MW heating has potential for use as an alternative fuel.

Acknowledgement

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