

TORREFACTION OF MOIST MUNICIPAL SOLID WASTE PELLETS USING CHAR OF BAGASSE AS A MICROWAVE ABSORBER

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Abstract

The torrefaction of moist municipal solid waste (MSW) pellets using char of bagasse as a microwave absorber (MA) is carried out in a microwave oven at the microwave power of 500-800 W for 12 min. After the torrefaction, moisture is completely removed from the MSW-pellet samples. The solid and energy yields of the torrefied MSW-pellet samples decrease, whereas the higher heating value (HHV) increases, with an increase in the microwave power and the addition of the MA. The hydrogen/carbon (H/C) and oxygen/carbon (O/C) mass ratios of the torrefied MSW-pellet samples decrease and tend towards those of coal. The torrefaction of the MSW pellets at the microwave power of 500 W with the addition of the MA is recommended as it yields the torrefied MSW-pellet samples with the highest HHV and energy yield.

Keywords: Torrefaction, municipal solid waste, microwave absorber, bagasse char

Introduction

Municipal solid waste (MSW) is the non-hazardous material generated from several human activities. MSW can be produced from the household, commercial, institutional, and industrial sectors (Laohalidanond *et al.*, 2015; Sun and Chungpaibulpatana, 2017). A fast economic development in several developing countries has led to rapid urbanisation and higher living standards (Khan *et al.*, 2016;

Song *et al.*, 2017). These result in a dramatic increase in the generation of MSW (Khan *et al.*, 2016; Zhao *et al.*, 2016; Song *et al.*, 2017). The generation of MSW in Bangkok, Thailand, for example, has increased continuously, from ~8,000 tons/day in 2005 (Sun and Chungpaibulpatana, 2017) to ~13,000 tons/day in 2017 (Pollution Control Department, 2018), or by more than 60%.

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Hence, it is desirable to have an effective technique to dispose of MSW in an economical and timely manner. MSW incineration is one of the favourable choices as it provides a quick way to reduce a large amount of MSW (Song *et al.*, 2017). Additionally, MSW incineration can generate heat and electricity, which can be sold to offset the MSW disposal cost (Zhao *et al.*, 2016; Song *et al.*, 2017). Problematically, however, due mainly to inadequate MSW disposal systems, MSW in Thailand usually contains a high amount of moisture (Laohalidanond *et al.*, 2015). Burning moist MSW reduces the incineration efficiency and can lead to the generation of several pollutants. Thus, it is necessary that moist MSW be pre-treated before being incinerated.

Torrefaction, a thermochemical process in an inert environment, can be used to pre-treat moist MSW. The typical temperature range of this process is 200-300°C (Basu, 2013), which can be considered relatively low. Thus, the pre-treatment using torrefaction can lead to a lot of energy savings

Several types of biomass have been torrefied at various conditions with the main objective to improve fuel qualities and combustion properties. Bridgeman *et al.* (2008) studied the torrefaction of canary grass, wheat straw, and willow at 230-290°C for 30 min in a laboratory-scale furnace and discovered that the torrefied biomass samples have lower amounts of moisture and volatile matter (VM). Additionally, the characteristics of the torrefied biomass were found to tend towards those of low-rank coals. In the work of Deng *et al.* (2009), agricultural residues, including rice straw and rape stalk, were torrefied in a vertical reactor at 200-300°C for 30 min. The results revealed that an increase in the torrefaction temperature led to a decrease in the solid yield (the ratio between the mass of the torrefied samples and that of the raw sample) and the amount of VM. The higher heating values (HHVs) of the torrefied agricultural residues increased by 15-17% when comparing to those of the raw agricultural residues. Chen *et al.* (2012) conducted experiments to investigate the torrefaction of 3 agricultural wastes, comprising

coffee residue, sawdust, and rice husk, in a tube furnace at 240 and 270°C for 0.5 and 1.0 h. The torrefied agricultural residues had higher HHVs, up to 38%, and their properties approached those of high-volatile coals.

Recently, it has been found that microwave irradiation is a promising choice as a heating technique for the torrefaction because it provides a rapid and uniform heating (Li *et al.*, 2016). Several types of biomass have been torrefied using microwave irradiation as a heating medium. Wang *et al.* (2012) performed experiments to investigate the effects of different parameters on the microwave torrefaction of rice husk and sugarcane residues and discovered that, with the microwave power of 250-400 W and the processing time of 4-30 min, the HHVs of these residues could be increased by 26-57%. The microwave torrefaction of rice straw and pennisetum was studied in the work of Huang *et al.* (2012). It was found that with only the microwave power of 150 W and the torrefaction time of 10 min, the HHV of the resulting biomass could be increased by 14%. The torrefied products had higher HHVs and lower hydrogen/carbon (H/C) and oxygen/carbon (O/C) ratios, which indicated that the combustion properties of the torrefied products were improved.

However, it was revealed by the studies of Menendez *et al.* (2002) and Zuo *et al.* (2011) that sewage sludge, which can be considered as MSW that contained a considerable amount of moisture, poorly absorbed microwave irradiation. Hence, the addition of a microwave absorber (MA), such as carbon black, silicon carbide (SiC), or a mixture of carbon black and SiC, was required to enhance the ability of highly moist MSW to absorb microwave irradiation (Menendez *et al.*, 2002; Liu *et al.*, 2011; Zuo *et al.*, 2011).

Nevertheless, carbon black and SiC are rather expensive and may not be available locally. Since Thailand is an agricultural-based country, agricultural residues are abundant, and these agricultural residues can be used to produce char, which can be considered carbon black. Thus, char produced from agricultural residues should be able to be used as an MA in

the microwave torrefaction of highly moist MSW.

Hence, it is the main purpose of this study to investigate the microwave torrefaction of moist MSW using the char of bagasse, a kind of agricultural residue, as an MA. The characteristics of the products obtained from the microwave torrefaction of moist MSW, with and without the addition of the MA, are examined.

Materials and Methods

The model type of MSW used in this study is cylindrical pellets of MSW, ~1 cm in diameter, ~1.5-1.7 cm long, and ~1 g in mass (each). The raw materials used to produce the model MSW consist of 40 wt.% scrap paper, 30% sawdust, 20% yard wastes, and 10% plastic wastes.

The proximate analysis of the raw MSW sample, comprising moisture, ash, VM, and fixed carbon (FC), is analysed following ASTM D3173, D3174, D3175, and D3172, respectively. The ultimate or elemental analysis of the raw MSW sample, including carbon (C), hydrogen (H), oxygen (O), and nitrogen (N), is analysed following ASTM D3176 using an elemental analyser (LECO, Series 628, LECO Corp., St. Joseph, MI, USA). The higher heating value (HHV) of the raw MSW sample is also determined following ASTM D5865, using an isoperibol bomb calorimeter (IKA, C6000, IKA-Werke GmbH & Co. AG, Staufen, Germany).

In order to prepare char of bagasse to be used as an MA in the present study, raw bagasse is heated at 500°C, in the absence of air, for 30 min in a muffle furnace. The resulting char, which contains no moisture or VM, is ground to the size of 60 mesh, using a ball mill, and kept in a sealed plastic bag for further use.

In each experiment, the MSW-pellet samples are weighed for ~1 g using a 4-decimal electric balance (Ohaus, PA 214, MilliporeSigma, Burlington, MA, USA) and put into a porcelain crucible. A pre-determined amount of water is carefully injected into the samples to adjust the moisture content of the samples to 40 wt.% of

the dry mass of the sample. Ground char of bagasse, the MA, in the amount of 40 wt.% of the dry mass of the samples, is added into the crucible containing the MSW-pellet samples, by pouring it around the samples. The crucible containing the wet MSW-pellet samples and ground char of bagasse is covered with a lid (to prevent air from entering into the crucible to burn with the samples during the torrefaction) and then placed in a microwave oven (ERG23SCW, Toshiba Corp., Tokyo, Japan) operated at 500-800 W for 12 min. After the torrefaction, the temperature of the torrefied samples is quickly measured using an infrared thermometer (66-IR Model Fluke Corp., Everett, WA, USA). The crucible containing the torrefied samples is taken out of the microwave oven, placed in a desiccator to allow it to cool down, weighed for its remaining mass, and then analysed for both its proximate and ultimate analyses and HHV, as *per* the raw MSW sample.

Results and Discussion

The results of the proximate and ultimate analyses, as well as the HHV, of the raw MSW sample are summarised in Table 1.

After the torrefaction, it is found that moisture is completely or nearly completely driven off from the torrefied samples, as illustrated in Table 2. This indicates that all of the torrefaction conditions employed in this study are adequate to remove moisture from the samples. The addition of char of bagasse as the MA leads to a complete removal of moisture from the samples, as also shown in Table 2.

The temperatures of all torrefaction conditions, as displayed in Figure 1, are well higher than 100°C, the boiling point of water. Thus, it is reasonable to infer that moisture is completely removed from the samples. It should be noted, however, that the temperatures of the torrefied samples indicated in Figure 1 might be lower than their actual temperatures by 30-50°C, due to a delay in the measurements of the temperatures of the torrefied samples as it is necessary to wait

until the door of the microwave oven is opened.

The solid yields, calculated using Equation (1) (Bridgeman *et al.*, 2008), of the torrefied samples at different torrefaction conditions are also shown in Figure 1.

$$\text{Solid yield} = \frac{m_{\text{torrefied MSW}}}{m_{\text{raw MSW}}} \times 100 \quad (\text{dry basis}), \quad (1)$$

where $m_{\text{torrefied MSW}}$ and $m_{\text{raw MSW}}$ are the mass of the torrefied and raw MSW samples, respectively.

The remaining amounts of ash, VM, and FC of the torrefied samples relative to their corresponding initial values are presented in Figures 2, 3, and 4, respectively.

From Figure 1, it is obvious that the solid yields of the torrefied samples, both with and without the addition of the MA, decrease with an increase in the microwave power. This is in accordance with the results from previous studies (Huang *et al.*, 2012; Wang *et al.*, 2012).

The final temperatures of the torrefied samples read from Figure 1 are ~150–240°C. When taking into account the fact that the

temperatures appearing in Figure 1 might be 30–50°C lower than the actual temperatures, the actual final temperatures of the torrefied samples should lie between 180–200 and 270–

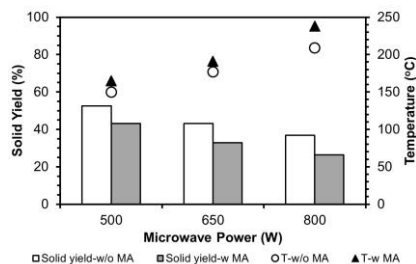


Figure 1. Solid yields and temperatures of the torrefied samples treated at different microwave powers for 12 min

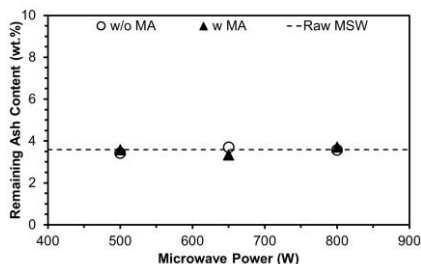


Figure 2. Remaining amounts of ash of the torrefied samples treated at different microwave powers for 12 min, compared to that of the raw MSW sample (dashed lines)

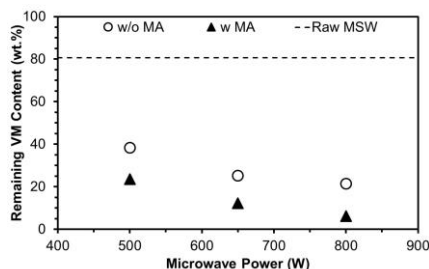


Figure 3. Remaining amounts of volatile matter (VM) of the torrefied samples treated at different microwave powers for 12 min, compared to that of the raw MSW sample (dashed lines)

Table 1. Proximate analysis, ultimate analysis, and higher heating value (HHV) of the raw MSW sample

Proximate analysis, dry basis (wt%)	
Ash	3.59
Volatile matter (VM)	80.68
Fixed carbon (FC)	15.73
Ultimate analysis, dry and ash-free (DAF) basis (wt%)	
Carbon (C)	44.16
Hydrogen (H)	5.63
Oxygen (O)	49.49
Nitrogen (N)	0.72
Heating value (MJ/kg)	17.38

Table 2. Remaining moisture contents in the torrefied MSW-pellet samples treated at different microwave powers for 12 min, compared to the initial moisture content in the raw MSW-pellet sample

Microwave power (W)	Moisture content (wt%)	
	Without MA	With MA
Initial moisture content	40	
500	0.25	0
650	0.03	0
800	0	0

290°C. Since the main components of the MSW-pellet samples used in this study are scrap paper, sawdust, and yard wastes, which can be considered lignocellulosic biomass, with the temperatures of this range (*i.e.* 180-290°C), most of the hemicellulose and to a lesser extent of the cellulose are decomposed and removed from the samples as VM, as reported by Bilgic *et al.* (2016) and Chen *et al.* (2015). This can be observed by decreases in the VM contents of the torrefied samples, as illustrated in Figure 3.

An increase in the microwave power leads to an increase in the amount of energy from microwave irradiation, which is indicated by increases in the torrefaction temperatures, as shown in Figure 1. With the higher amount of energy, a higher amount of VM is removed,

thus resulting in the lower remaining amounts of VM in the samples. This is in good agreement with the work of Wang *et al.* (2012).

Since the final temperatures of the torrefied samples are lower than 300°C, whereas the decomposition of lignin takes place within the temperature range of 280-500°C, as indicated by Deng *et al.* (2009), most of the lignin is still retained in the samples as FC. Additionally, since ash is not removed from the samples by the torrefaction, it is also retained in the samples.

When considering the remaining amounts of ash and FC relative to their corresponding initial values, it is found that the percentages of ash and FC, appearing in Figures 2 and 4, respectively, are relatively constant. This confirms that ash and FC are mainly retained in the torrefied samples.

The addition of char of bagasse as the MA enhances the ability of the samples to absorb microwave irradiation, which results in an increase in the torrefaction temperature, as depicted in Figure 1. An increase in the torrefaction temperature, in turn, leads to more removal of hemicellulose and cellulose from the samples as VM, thus resulting in decreases in the VM content, as illustrated in Figure 3, and the solid yield, as shown in Figure 1.

The ultimate analysis, comprising carbon (C), hydrogen (H), and oxygen (O), of the torrefied samples treated at 500-800 W for 12 min, with and without the addition of the MA, and that of the raw MSW sample are shown in Figure 5. Note that, since the amount of N in the MSW samples used in this study is negligibly low, the amounts of C, H, and O in the samples presented in Figure 5 are normalised by dividing the corresponding amount of C, H, or O by the summation of the total amounts of C, H, and O.

It is found that, after the torrefaction, the percentage of C in the torrefied samples increases, whereas the percentage of O decreases, while the percentage of H insignificantly changes. The percentage of C increases from 44.5 wt.% for the raw sample to ~50-60 wt.% for the torrefied samples, or increases by ~12-35%. The percentage of O decreases from 49.8

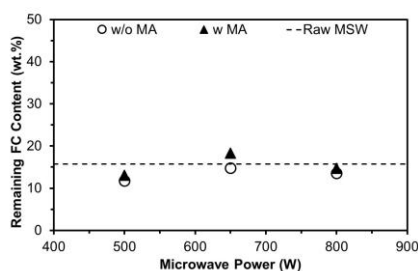


Figure 4. Remaining amounts of fixed carbon (FC) of the torrefied samples treated at different microwave powers for 12 min, compared to that of the raw MSW sample (dashed lines)

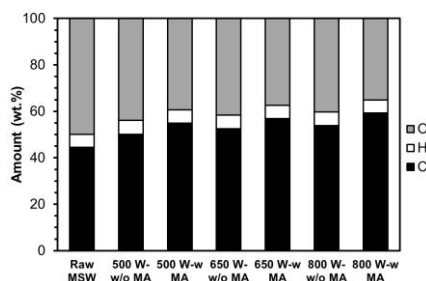


Figure 5. Amounts of carbon (C), hydrogen (H), and oxygen (O) of the torrefied samples treated at different microwave powers for 12 min, compared to those of the raw MSW sample

wt.% to ~35-44 wt.%, or decreases by 12-30%. The percentage of H of the torrefied samples is in the range of 5.5-6.0 wt.%, compared to that of the raw sample of 5.7%. This agrees with the results reported by Wang *et al.* (2012). It is also found that the addition of the MA causes the percentage of C in the torrefied samples to increase, but leads to a decrease in the percentage of O. The addition of the MA, however, has an insignificant effect on the remaining amount of H.

As indicated previously, an increase in the microwave power and the addition of the MA causes the torrefaction temperature to increase, thus enhancing the decomposition of hemicellulose and cellulose from the torrefied samples in the form of VM. Since VM contains more O than C, as mentioned by Chen *et al.* (2015), the removal of VM causes the percentage of O in the torrefied samples to decrease. However, as also discussed previously, an increase in the microwave power and the addition of the MA are found to have a negligible effect on the remaining amount of FC of the torrefied samples. Since C is the main component of FC, as indicated by Basu (2013), the amount of C in the torrefied samples is rather constant. As the amount of O is decreased, while the amount of C remains relatively constant, the relative amount or the percentage of C in the torrefied samples is found to increase.

The mass ratios between H/C and O/C of the torrefied samples treated at various torrefaction conditions are plotted in Figure 6. Since the percentage of C in the torrefied samples increases, whereas the percentage of O is reduced, and the percentage of H is relatively constant, the H/C and O/C mass ratios of the torrefied samples are found to decrease. The H/C and O/C mass ratios of the torrefied samples decrease with an increase in the microwave power and the addition of the MA. The decreases in the H/C and O/C mass ratios of the torrefied samples are found to be relatively linear, which are in good agreement with the results reported by Chen *et al.* (2012). When comparing the H/C and O/C mass ratios of the torrefied samples to those of sub-bituminous coal and lignite, obtained from the

work of Yi *et al.* (2017), it reveals that the H/C and O/C mass ratios of the torrefied samples tend towards those of coal. This indicates that the combustion properties of the torrefied MSW samples are improved.

The HHV of the torrefied samples, depicted in Figure 7, is found to increase with an increase in the microwave power and the addition of the MA.

As described previously, the percentage of C in the torrefied samples is found to increase, whereas the percentage of O is decreased, with an increase in the microwave power and the addition of the MA, as illustrated in Figure 5. It is reported by Chen *et al.* (2011) that C plays an exothermic role (*i.e.* releases energy) when a fuel is burned, whereas O plays an endothermic role (*i.e.*

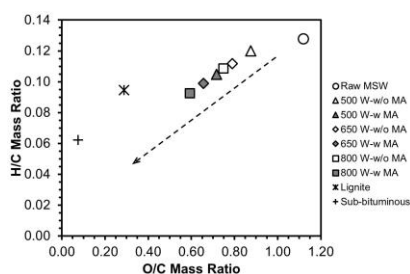


Figure 6. The H/C and O/C mass ratios of the torrefied samples treated at different microwave powers for 12 min, compared to those of the raw MSW sample, lignite, and sub-bituminous coal

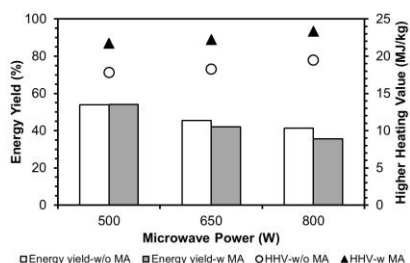


Figure 7. Energy yields and higher heating values (HHVs) of the torrefied samples treated at different microwave powers for 12 min

consumes energy). Thus, an increase in the percentage of C and a decrease in the percentage of O lead to an increase in the HHV of the torrefied samples.

Even though the microwave torrefaction yields the torrefied samples with higher HHV, as shown in Figure 7, the solid yield, which indicates the remaining mass of the torrefied samples, decreases after the torrefaction, as appeared in Figure 1.

To account for an increase in the HHV and a decrease in the solid yield at the same time, the energy yield, which can be computed using Equation 2, is introduced (Bridgeman *et al.*, 2008; Chen *et al.* 2011):

$$\text{Energy yield} = \text{Solid yield} \times \frac{\text{HHV}_{\text{torrefied MSW}}}{\text{HHV}_{\text{raw MSW}}}, \quad (2)$$

where $\text{HHV}_{\text{torrefied MSW}}$ and $\text{HHV}_{\text{raw MSW}}$ are the higher heating values of the torrefied and raw MSW samples, respectively.

The energy yield is the ratio between the total amount of energy of the torrefied samples and that of the raw sample. It is used to assess the efficiency of the torrefaction (Huang *et al.*, 2012; Wang *et al.*, 2012). The higher value of the energy yield means that the higher amount of energy is retained in the torrefied samples.

Table 3. Solid yields and energy yields of the torrefied samples treated at different microwave powers for 12 min

Microwave power (W)	Solid yield (%)		Energy yield (%)	
	Without MA	With MA	Without MA	With MA
500	52.51	43.19	53.90	54.02
650	43.15	32.84	45.41	42.00
800	36.87	24.63	41.30	35.55

It is found that the energy yield displays the same trend as the solid yield in the manner that the energy yield decreases with an increase in the microwave power and the addition of the MA. Additionally, the energy yield is found to be always higher than the solid yield, as illustrated in Table 3, which is in accordance with the findings reported in the

previous studies (Chen *et al.*, 2012; Huang *et al.*, 2012; Wang *et al.*, 2012).

An increase in the microwave power leads to an increase in the difference between the solid yield and the energy yield of the torrefied samples, as shown in Table 3. Interestingly, it is found only for the torrefaction at 500 W that the energy yields of the torrefied samples, with and without the addition of the MA, are higher than 50% and that the energy yield of the torrefied samples with the addition of the MA is higher than that without the addition of the MA (54.02% vs 53.90%). Additionally, the torrefaction at this condition yields the torrefied samples with the highest heating value and energy yield. Hence, the torrefaction at this condition is recommended.

Conclusions

The results obtained from the microwave torrefaction of moist MSW-pellet samples treated at the microwave powers of 500-800 W for 12 min, with the addition of char of bagasse as the microwave absorber (MA), indicate that moisture is completely driven off from the samples, while volatile matter (VM) is partially removed from the samples. An increase in the microwave power and the addition of the microwave absorber (MA) cause the torrefied samples to have lower VM content and solid yield, lower H/C and O/C mass ratios, which tend towards those of coal, and higher HHV. The torrefaction at 500 W with the addition of the MA is recommended as it results in the torrefied samples with the highest heating value and energy yield.

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