Biochar Preparation from Simulated Municipal Solid Waste Employing Low Temperature Carbonization Process

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Abstract. This paper presents an investigation on carbonization process of simulated municipal solid waste (MSW). Simulated MSW consists of a representative of food residue (68%), plastic waste (20%), paper (8%), and textile (4%). Laboratory-scale carbonization was performed in this study using a vertical-type pyrolyzer varying carbonization temperature (300, 350, 400, and 450 °C) and heating rate (5, 10, 15, and 20 °C/min). Appearance of the biochar product was in black and the volume was significantly reduced. Low carbonization temperature (300 °C) might not completely decompose plastic materials in MSW. Results showed that the carbonization at the temperature of 400 °C with the heating rate of 5 °C/min was the optimal condition. The yield of biochar from the optimal process was 50.6% with the heating value of 26.85 MJ/kg. Energy input of the process was attributed to water evaporation and the decomposition of plastics and paper. Energy output of the process was highest at the optimal condition. Energy output and input ratio was around 1.3-1.7 showing the feasibility of the carbonization process in all heating rate condition.

1. Introduction
One of the consequences of growing population and economic expansion is a waste management problem. Urbanization causes an increase of municipal solid waste (MSW). A systematic management of MSW is necessary to maintain good condition of the city or village. MSW is produced by households or residential areas, community, commercial area, markets, and other human activities. It excludes industrial, hazardous, construction, and demolition waste. In general, the MSW composition is organic that is biodegradable material such as food residues and yard waste; paper waste including scraps paper, newspapers, magazines, bags, packaging paper; plastic waste such as bottle, packaging, containers, and bags; glass product, for example, bottles and containers; metal in form of cans, foils, and other containers or parts; others could be textiles, leathers, ash, rubber, other inert materials. Considering waste-to-energy routes (WTERs) as a solution, waste materials turn out to be attractive assets. Unusable waste materials, such as municipal solid waste from residence [1,2] can be used for energy purpose. Alternative to waste incineration that is one of the most common method of waste elimination, carbonization process is a promising conversion process. It does not convert the MSW directly to energy but turn them into a valuable material that can be handle easily. After carbonization, the biochar product can be used for many applications such as solid biofuel and soil amendment. Biochar is generally produced from agricultural waste materials or biomass using carbonization process. Biomass residues, apricot stone, hazelnut shell, grapeseed, and chestnut shell, have been used...
to produce biochar and bio-oil and it was found that the biochar products contained high carbon content and high heating value while the bio-oil needs some upgrading process before utilization [3]. This paper investigated biochar production from simulated MSW using carbonization process. Major composition of MSW sample was tested using representative materials. Carbonization process was performed at laboratory-scale level. Temperature and heating rate of the carbonization were varied. Appearance and product yield were studied to find the optimal condition. Moreover, energy input, energy output, and energy output to input ratio were calculated. This process analysis can give information on feasibility of the process.

2. Material and methods

2.1. Raw materials

Sample used in this study was a simulated municipal solid waste (MSW) as shown in Fig. 1. The major waste composition in Thailand based on our previous study was organic, plastic, paper, and textile. Thus, the simulated MSW composition was food residue (68%), plastic waste (20%), paper (8%), and textile (4%) [4]. Plastic sample consists of PET 4%, HDPE 12%, and PP 4%. Chemical composition of the raw sample from elemental analysis (ASTM D5373) was 43.4% carbon, 6.3% hydrogen, 1.4% nitrogen, and 48.8% oxygen and from proximate analysis (ASTM D7582) was 77.8% of volatile matter, 14.6% of fixed carbon, and 7.6% of ash. Moisture of the raw sample was 65% and heating value (ASTM D5865) was around 20 MJ/kg in dry basis. Raw material was cut into small size roughly 1-2 cm while its density was very low.

![Figure 1. Simulated municipal solid waste for carbonization process.](image)

2.2. Carbonization

Carbonization experiment was done at laboratory-scale level using a vertical-type pyrolyzer with the PID controller and other equipment as shown in Fig. 2. For each experiment, the sample was filled in the reactor about 50 g and the nitrogen gas was injected 200 ml/min. The target temperature was (300, 350, 400, and 450 °C) and heating rate (5, 10, 15, and 20 °C/min). The duration of carbonization process was about 1 hour. The carbonization test was firstly performed at the heating rate of 25 °C/min with variation of temperature to check the optimal temperature condition then the variation of the heating rate was done for final optimization. After finished the experiment, the reactor was left to cool down. Then, biochar was taken out from the reactor. Each condition was duplicated.

2.3. Energy balance

Energy input of the process was energy used to heat the sample including sensible heat of solid phases (Eq.1), sensible heat of liquid phase (Eq.2), latent heat of melting (Eq.3) and latent heat of vaporizing (Eq.4) of each material. Summation of Eq.1, Eq.2, Eq.3, and Eq.4 obtains total energy need for carbonization process. The assumption of the parameters in all equations is presented in Table 1 where
Q is an amount of heat (kJ); m is mass (kg); $T_m$ is melting temperature (°C); $T_g$ is vaporization temperature (°C), $T_0$ is room temperature (°C); $L_m$ is latent heat of melting (kJ/kg); and $L_g$ is latent heat of vaporization (kJ/kg); $c_p$ is specific heat capacity (kJ/kg•K).

\[
Q_s\text{ (solid)} = mc_p(T_m - T_0) \\
Q_s\text{ (liquid)} = mc_p(T_g - T_m) \\
Q_m = mL_m \\
Q_g = mL_g
\]

Energy output from the process was energy in biochar and calculated by multiplying mass of biochar product and heating value of the sample. Energy output to input ratio was finally calculated. It determined feasibility of the process.

**Figure 2.** Laboratory-scale apparatus for carbonization process: (1) Pyrolyzer; (2) Nitrogen gas tank; (3) Piping system; (4) Exhaust hood; (5) PID controller; (6) Gas condenser.

**Table 1.** Summary of parameters and energy input [5-7].

|       | $c_{p,\text{solid}}$ [kJ/kg•K] | $c_{p,\text{liquid}}$ [kJ/kg•K] | $L_m$ [kJ/kg] | $L_g$ [kJ/kg] | $T_m$ [°C] | $T_g$ [°C] | $Q_s\text{ (solid)}$ [kJ] | $Q_s\text{ (liquid)}$ [kJ] | $Q_m$ [kJ] | $Q_g$ [kJ] | $Q_{\text{total}}$ [kJ] |
|-------|-----------------------------|-------------------------------|--------------|--------------|-------------|-------------|-------------------|-------------------|-------------|-------------|-------------------|
| PP    | 1.6                         | 2.1                           | 209          | 1900         | 160         | 354         | 0.4               | 0.8               | 0.4         | 3.8         | 5.5               |
| PET   | 1.1                         | 1.6                           | 139          | 1400         | 260         | 392         | 0.5               | 0.4               | 0.3         | 2.8         | 4.0               |
| HDPE  | 2                           | 2.7                           | 245          | 2200         | 130         | 380         | 1.3               | 4.1               | 1.5         | 13.2        | 20.0              |
| Textile | 1.3                         | -                             | 3200         | -            | 300         | 0.7         | 0                 | 0                 | 6.4         | 7.1         |                   |
| Paper | 1.2                         | -                             | 3200         | -            | 300         | 1.3         | 0                 | 0                 | 12.8        | 14.1        |                   |
| Food  | 1.4                         | -                             | 3200         | -            | 300         | 0.8         | 0                 | 0                 | 6.3         | 7.1         |                   |
| Water | -                           | 4.2                           | 2300         | -            | 100         | 0           | 10.08             | 0                 | 73.6        | 83.7        |                   |

3. Results and Discussion

3.1 Appearance of the product

Appearance of biochar Fig. 3 illustrates the appearance of biochar obtained from carbonization process. Biochar product was relatively uniform and its color was black. When comparing the effect of carbonization temperature, the overall appearance was similar; however, low temperature carbonization (300 °C) cannot decompose the plastic material as the plastic sample was melt and accumulated (data not shown). The biochar obtained from simulated MSW was easier for grinding
compared to the original material. For example, the plastic HDPE or PP from plastic bag or plastic container are difficult to reduce the size. Thus, using carbonization process can improve physical property of the material. The volume of the final product was significantly reduced.

![Image](image_url)

**Figure 3.** Appearance of biochar from carbonization process of simulated MSW

3.2 Yield of the product

Effect of temperature and heating rate on yield of the biochar at the beginning, the heating rate was fixed at 25 °C/min and the carbonization temperature was varied. Yield of the biochar is presented in Fig. 4a. From production curve, the carbonization temperature that gave the highest biochar yield was 400 °C at 20.9% (dry basis yield). When the carbonization temperature was further increased to 450 °C, the yield of biochar was reduced. As temperature increases, the volatile matter in the sample released faster resulting in the increasing of gaseous products. These gaseous products can be either condensable or non-condensable gas and they could be recovered for additional value.

![Graph](graph_url)

**Fig. 4** Yield of biochar from carbonization process: (a) at 25 °C/min with variation of temperature; (b) 400 °C with variation of heating rate.

Then, the heating rate of the carbonization process was varied at the temperature of 400 °C and the results show in Fig. 4b. Yield of biochar can be increased to 50.6% at the heating rate of 5 °C/min while the increasing of heating rate reduces the yield of the product. In general, the high heating rate was used for pyrolysis process aiming to obtain the oil product. Thus, to produce biochar, low heating rate was preferred.

3.3 Energy balance of the process

Detail calculated results of energy input is presented in Table 1. It can be observed that the largest amount of energy was utilized for water evaporation while heating HDPE and paper consumed significant amount of energy. Energy balance of the process is shown in Table 1. Recovered energy in biochar was around 26-29 kJ/kg and the higher heating rate could slightly increase the heating value of the biochar. However, high heating rate negatively affected the yield of biochar. Since lower yield of
biochar was obtained when increases the heating rate, the energy yield in the product was lowered. It should be noted that the energy output from the process was not only in the biochar, but also in the gas or recovered oil. These products could increase the energy output of the system. The process with 5 °C/min heating rate was the optimal as the energy output was the highest. This resulted in the highest energy output/input ratio of 1.65 showing highest feasibility of the process. High heating rate condition gave net energy output from the carbonization process.

Table 2. Energy balance of the process

| Heating rate [°C/min] | Heating value of biochar [MJ/kg] | Energy output [MJ/kg MSW] | Energy input [MJ/kg MSW] | Energy output/input ratio |
|-----------------------|---------------------------------|---------------------------|--------------------------|--------------------------|
| 5                     | 26.85                           | 4.67                      | 2.83                     | 1.65                     |
| 10                    | 28.45                           | 3.98                      |                          | 1.41                     |
| 15                    | 29.42                           | 3.94                      |                          | 1.39                     |
| 20                    | 28.38                           | 3.63                      |                          | 1.28                     |

4. Conclusion

Carbonization process was applied to simulated MSW that consists of food residue (68%), plastic waste (20%), paper (8%), and textile (4%). Carbonization was performed at the temperature of 300, 350, 400, and 450 °C and the heating rate of 5, 10, 15, and 20 °C/min. Energy balance of the process was investigated to observe the feasibility of the process. Conclusion can be made as follows:

1. Appearance of the biochar obtained from carbonization process was in black and the volume was significantly reduced. Low carbonization temperature might not completely decompose plastic materials in MSW.

2. Optimal temperature in this study was 400 °C with the heating rate of 5 °C/min. This condition gave the highest yield of biochar at 50.6% dry basis. The heating value of biochar from this optimal condition was 26.85 MJ/kg.

3. Increase the carbonization temperature could help increase the yield of the biochar; however, too high temperature gave the opposite result. Lower heating rate can increase the biochar yield.

4. Energy input of the process was attributed to water evaporation and the decomposition of plastics and paper. Energy output of the process was highest at the optimal condition. Energy output and input ratio was around 1.3-1.7 showing the feasibility of the carbonization process in every heating rate condition.

5. References

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