Parametric and optimization studies for biochar production from municipal solid wastes (MSW) via pyrolysis

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Abstract. The accumulation of municipal solid wastes (MSW) and the negative implications of using fossil fuels are some of the current environmental issues in the Philippines. Hence, this study aimed to utilize MSW by converting it into biochar through pyrolysis and maximize biochar production for energy application. The effects of pyrolysis parameters such as temperature and holding time on biochar yield were initially determined using 2⁰ factorial experiment. Results showed that both factors had negative effects on biochar yield where in temperature had a relatively higher impact. For the optimization study, Response Surface Methodology (RSM) was performed to determine the optimum pyrolysis conditions for maximum biochar production. The optimum conditions were found to be 300°C and 20 min holding time resulting to maximum biochar yield of 69.64 % by wt. Biochar characteristics were evaluated in terms of higher heating value (HHV), proximate and elemental analyses to determine its suitability as alternative fuel. The HHV of biochar obtained at optimum conditions was about 15.82 MJ/kg which is higher compared to that of the raw MSW (14.42 MJ/kg) and biochar obtained at extreme conditions (13.03 MJ/kg). Moreover, the energy recovery at optimum conditions based on biochar yield was about 76.37% which was also higher compared to that of the biochar obtained at higher temperature and holding time which was about 32.75 %. Using van Krevelen diagram, MSW-derived biochar at the optimum conditions can be classified as lignite, while MSW-derived biochar at extreme conditions is comparable to anthracite coal.

1. Introduction
The rapid increase in municipal solid wastes (MSW) generation in the Philippines results to several environmental and health issues. According to the Department of Environment and Natural Resources[1], the average waste generation rate in the country in 2010 was approximately 0.40 kg/capita/day resulting to a total waste generation of about 13.48M tons. The total waste generation in the country is projected to increase to about 16.63M tons by the year 2020 from 15.02M tons in 2015.

To address the problem associated with MSW, Republic Act 9003 also known as the Ecological Solid Waste Management Act of 2000 was enacted. It involves the hierarchy of waste management including waste avoidance, reduction, reuse, recycle, and recovery, before systematic collection,
transport, and disposal[1]. Local government units (LGUs) were mandated to operate materials recovery facilities (MRFs) for recycling and composting waste. However, more than a decade after the enactment of the law, only around 10.7% of the MSW generated in the country are being recycled or composted, while a large portion of the wastes still ends up in dumpsites[2]. The accumulation of wastes in open dumpsites and illegal burning of wastes have led to various environmental problems including groundwater and soil contamination, and greenhouse gas (GHG) emissions[3].

Aside from increasing waste generation and its negative impacts to the environment, the depleting supply of fossil fuels, which at present serves as the main source of energy, is another problem that the country is facing. In 2017, the country’s demand for energy as electricity was 13,789 MW which was 3.9% higher than the demand in 2016[4]. Increasing use of these non-renewable resources will eventually lead to a lower supply of energy in the future; thus, the search for alternative sources of energy is deemed necessary. Moreover, burning of these fossil fuels to produce energy contributes to GHG emission which causes global warming leading to climate change[5].

One alternative source of energy is MSW. It has high carbon and low oxygen contents and high caloric value of about 13.75 MJ/kg making it a potential source of solid fuel[6][7]. Moreover, MSW is a renewable and sustainable source of energy. In fact, several countries such as Japan and United States use their solid waste for energy production through waste-to-energy (WtE) technologies including landfill gas recovery, biological conversion, and thermochemical conversion methods. Also, converting MSW via WtE technologies can significantly reduce the volume of waste for final disposal as well as decrease dependency on fossil fuels for energy production. One thermal conversion technology is pyrolysis which is operated without oxygen to produce bio-oil, biochar, and synthetic gas[8]. To favor biochar production from MSW, the process should be operated at low temperature and short holding time[9]. Carbon enrichment of biochar during pyrolysis results to an increase in its higher heating value (HHV) compared to the unprocessed biomass[10]. This attributes to the high energy content of biochar derived from MSW which makes it a potential alternative to fossil fuels for energy generation.

In this study, MSW was used as feedstock for biochar production using slow pyrolysis. Initially, the MSW collected was characterized based on HHV, proximate analysis, and elemental composition. The effects of several parameters including temperature and holding time on biochar yield were evaluated. After determining the significant factors, pyrolysis conditions were optimized for maximum biochar yield. The biochar obtained at optimum conditions was characterized in terms of energy content and composition and compared to the MSW feedstock. Lastly, van Krevelen diagram was used to assess the potential of MSW-derived biochar as energy source.

2. Methods

2.1. MSW collection and pre-treatment
The components of MSW were separately collected from markets, households, and various establishments around Los Baños, Laguna, Philippines and stored in their corresponding containers. Each MSW component was sun-dried and was oven-dried at 60°C for 48 hr. The fully dried MSW components were separately crushed using a hammer mill and a multi-purpose shredder. The dried and ground MSW were placed and stored in an airtight container to prevent absorption of moisture. Each component of ground MSW was then sieved using USA Standard Testing Sieves with mesh numbers 10 and 20 to obtain MSW samples with particle size ranging from 0.85 mm to 2.0 mm. After sieving, MSW sample was composed of food waste (32.78%), plastic (8.52%), paper (10.62%), glass (7.01%), other organics (31.85%), and inorganics (9.23%).

2.2. MSW characterization
Complete proximate analysis of the ground MSW was determined at the Industrial Technology Development Institute, Department of Science and Technology (DOST-ITDI) following the modified ASTM D 1762. For the elemental analysis, a Thermo Scientific Flash 2000 CHNS-O Analyzer was
used. Lastly, higher heating value (HHV) of the dried sample was experimentally determined using a Parr 6200 Calorimeter at DOST-ITDI and ASTM D 3286 was followed.

2.3. Slow pyrolysis experiment

The pyrolysis experiment was adopted from the study of Requiero\textsuperscript{11}. For each run, 5 g of the dried and ground MSW sample was placed in a stainless-steel reactor. It was then purged with nitrogen gas for 2 min through the holes at the cap to ensure the absence of oxygen and to release other inert gases\textsuperscript{12}\textsuperscript{13}. The reactor was placed and heated at the desired temperature inside the VULCAN® A-550 analog control furnace. After reaching the target temperature, the pyrolysis set-up was held at the desired temperature and holding time. When the holding time was reached, the heater was turned off for the set up to cool down to room temperature before collecting the biochar. The yield of biochar was calculated using Equation (1).

\[ Y_{mass} = \frac{m_b}{m_{MSW}}(100) \]  

where:

- \( m_b \): mass of collected biochar (g)
- \( m_{MSW} \): mass of MSW sample
- \( Y_{mass} \): mass yield of biochar (%)

2.4. Experimental design and statistical analysis

2.4.1. Factorial Experimental Design

For the parametric study, two-factor two level (2\(^2\)) factorial experimental design with four center points was used to determine the significant factor/s affecting the biochar yield and to determine if an optimum is within the considered low and high levels. The low and high levels for temperature were 400 °C and 600 °C while 30 min and 120 min were set for holding time based from the studies of Requiero\textsuperscript{11} and Jin et al.\textsuperscript{12}. Analysis of Variance (ANOVA) at 95 % confidence interval was used to determine if the model and the factors are significant.

2.4.2. Response Surface Methodology

Response Surface Methodology (RSM) using face-centered Central Composite Design (CCD) was used to determine the maximum biochar yield. From the parametric study, it was found out that the biochar yield might still increase by increasing the levels of the two factors; thus, adjustments were made. The adjusted low and high levels for temperature were 300 °C and 600 °C while 20 min and 120 min for holding time. After performing the optimization runs, numerical optimization was conducted. The goal for the optimization includes maximizing biochar yield at temperature and holding time ranging from their respective low and high limits.

2.5. Biochar characterization

The characteristics of biochar obtained at the optimum conditions were evaluated using proximate analysis, elemental composition, higher heating value (HHV), surface area, and morphology. Same procedures for MSW characterization were followed for the compositional analyses and HHV. For surface area determination, Nitrogen Sorption Analysis was used while field emission-scanning electron microscope was used for the morphology of the biochar.

2.6. Energy recovery and classification using van Krevelen diagram

The energy recovery of biochar was calculated using the following equation as suggested by Bergman et al. as cited by Yuan et al.\textsuperscript{14}.
\[ Y_{\text{energy}} = Y_{\text{mass}} \frac{HHV_b}{HHV_{\text{MSW}}} \]  

where:
- \( HHV_b \) is the higher heating value of biochar (MJ/kg)
- \( HHV_{\text{MSW}} \) is the higher heating value of raw MSW (MJ/kg)
- \( Y_{\text{energy}} \) is the energy recovery (%)

Moreover, van Krevelen diagram was used to assess the potential of biochar derived from MSW as energy source. In the plot, biochar produced was categorized into which solid fuel it is comparable to by plotting the oxygen to carbon ratio (O/C) and hydrogen to carbon ratio (H/C). The H, C, and O values used were from the elemental analysis of biochar at the optimum conditions.

3. Results and Discussion

3.1. MSW characteristics

Characterization of MSW allows the assessment of the quality of the feedstock as a potential energy source. In this study, proximate analysis, elemental composition, and higher heating value of the raw MSW were determined as shown in Table 1.

Table 1. Elemental composition of raw MSW and biochar produced at different pyrolysis conditions.

| CHARACTERISTICS | RAW MSW | MSWB300 | MSWB600 |
|----------------|---------|---------|---------|
| Proximate Analysis (%) | | | |
| MC | 8.5 | 1.98 | 0.59 |
| VCM (dry basis) | 57.4 | 48.8 | 20.36 |
| Ash (dry basis) | 26.4 | 27.6 | 38.37 |
| FC (dry basis) | 16.2 | 23.6 | 41.27 |
| C | 36.89 | 51.02 | 55.54 |
| Elemental Analysis (%) | | | |
| H | 4.18 | 4.58 | 1.03 |
| O | 31.74 | 15.93 | 4.22 |
| N | 0.79 | 0.87 | 0.84 |
| S | - | - | - |
| HHV (MJ/kg) | 14.42 | 15.82 | 13.03 |

3.1.1. Proximate Analysis

Proximate analysis was performed to determine the moisture content, volatile combustible matter (VCM), ash, and fixed carbon of MSW. A low moisture content of about 8.5 % by wt was obtained. According to Akhtar and Amin[15], if pyrolysis is to be conducted, the moisture content of the biomass should be less than 30 % by wt; hence, the MSW sample can be a suitable feedstock for pyrolysis based on its moisture content. A low moisture content of biomass is necessary for pyrolysis; otherwise, the energy supplied during the process will be mostly used up for moisture removal from the feedstock instead of raising the temperature of the system for thermochemical conversion[16]. A high VCM in the feedstock may result to gaseous formation during pyrolysis due to its devolatilization which can decrease biochar yield. The VCM obtained was relatively higher compared to the other components which is probably due to the high amount of organic matter in the sample. However, VCM content of the raw MSW (57.4%) is lower than that of the MSW (82.0%) in the study of Yuan et al.[14]. This is probably due to high percentage of plastics (~34 % by wt) in that study compared to that of the MSW in this study (8.52 % by wt). Ash is the grayish solid residue after the complete combustion of the sample and its content varies depending on the feedstock type. The ash content (26.4%) of the sample is high probably due to glass and inorganic components of the raw MSW unlike in the MSW sample in Yuan et al.[14] which resulted to lower ash content (7.6%). According to Shariff et al.[17], biochar yield might
increase due to a high ash content of the feedstock since this non-combustible matter will be left in the solid residue after pyrolysis. Additionally, the ash content of the raw MSW was higher than the fixed carbon (16.2%). This is opposite with the result of the study of Yuan et al.\[14\] wherein the fixed carbon content (10.4%) was greater than its ash content. A feedstock which has high fixed carbon content is preferable since it can increase biochar yield as well as improve its quality as solid fuel\[18\]. According to Sadiku et al.\[19\], fixed carbon content of the biomass act as the heat contributor during thermal conversion process.

### 3.1.2. Elemental Composition

Elemental analysis helps to determine the potential fuel properties of the feedstock and to assess the content of biomass for evaluating its environmental impact when put into use\[20\]. Based from Table 1, C and O contents of raw MSW were relatively higher compared to the other elemental components due to its high organic and plastic constituents. A high C content of raw MSW can increase biochar yield after pyrolysis and can also contribute to a better quality of biochar in terms of its coal rank. Additionally, formation of gases during pyrolysis can be attributed to high O and H contents of the raw sample. On the other hand, N content was in trace amounts of about 0.79 %; and as for S, no significant amount was detected. A negligible S and low N contents in the feedstock are favorable so that SO\(_x\) and NO\(_x\) emission will be minimal during pyrolysis\[17\]. In the study of Jin et al.\[12\], all elemental components (44.7 %C, 12.9 %H, 38.5 %O, 1.4 %N, 1.1 %S) of MSW were higher compared to that of the MSW sample in this study as shown in Table 1. This is probably due to the low ash content of MSW in Jin et al.\[12\] which implies higher VCM and FC making its elemental composition to also increase.

### 3.1.3. Higher Heating Value

Higher heating value (HHV) is the amount of heat released after the complete combustion per unit of biomass\[23\]. According to Sukiran et al.\[6\], a high HHV implies that the material has a high energy content which makes it suitable to act as a fuel. Based from the result, the HHV of MSW was about 14.42 MJ/kg which is comparable to the overall HHV (13.75 MJ/kg) of MSW in the study of Caraos\[7\]. The obtained value was relatively higher than the usual HHV of MSW ranging from 8 MJ/kg to 11 MJ/kg\[22\]. A high value of HHV can be possibly due to the plastic present in the sample. According to Sipra et al.\[23\], chlorine-free plastics have high HHV contributing to a high value for the whole MSW sample.

### 3.2. Factors Affecting Biochar Yield from MSW

Based from Analysis of Variance (ANOVA) at 95 % confidence interval (\(\alpha=0.05\)), both factors have significant effects on biochar yield; however, temperature has a greater impact on the yield compared to holding time.

#### 3.2.1. Effect of Temperature

Biochar production is influenced by several parameters; however, temperature (p-value < 0.0001) has the highest impact on the yield as well as on the characteristics of biochar\[24\]\[25\]. A decreasing trend in biochar yield at an increasing temperature from 400°C (50.85% by wt) to 600°C (39.46% by wt) was observed at 30 min holding time. Same observation was obtained in the study of Park et al. as cited by Sharma et al.\[23\] in which the char yield from wood biomass decreased from 31% to 17% when the temperature was increased from 365°C to 605°C. This is mainly because at higher pyrolysis temperature, more volatiles are released from the material leading to a reduction in the mass of the solid residue after the process\[24\]. Additionally, higher temperatures cause the bond of the volatile components to break, thus forming more gases than char\[16\]. Though lower temperatures favor biochar yield, incomplete decomposition and devolatilization might occur resulting to a higher yield but with unpyrolyzed or partially pyrolyzed substances\[24\].

#### 3.2.2. Effect of Holding Time
Based from the results, increasing the holding time from 30 min to 120 min at 400°C decreased the biochar yield from 50.85 % by wt to 47.92 % by wt, respectively. Though the holding time has less impact on the yield than temperature, it is still a significant parameter based from the statistical analysis (p-value < 0.0001). Same result was reported in the study of Suman and Gautam[26] for the pyrolysis of wooden dust, rice husk, and sugarcane bagasse. A decreasing trend on the biochar yields of the three feedstocks was observed at an increasing time of 1 hr to 3 hr at a constant temperature. According to Ningbo et al.[27], further decomposition of volatile component of the biomass occurs when the pyrolysis time is increased, thus favoring the release of gases and decreasing the char yield.

3.2.3. **Optimum Conditions for Biochar Production from MSW**

Since it was observed from the factorial experiment that decreasing the temperature and holding time increases the yield, the low levels for both factors were adjusted in the optimization part to determine if the biochar yield will still increase. The low levels of temperature and holding time were decreased to 300°C and 20 min, respectively. From the statistical analysis, no peak was observed implying that there was no optimum found within the range of values of the factors. However, the highest yield obtained was considered the optimum value for the biochar yield. This is because the low level of the temperature cannot be further adjusted since temperatures less than 300°C are considered torrefaction rather than slow pyrolysis[28]. Moreover, shortening the holding time under 20 min might result to the presence of unpyrolyzed substances in the biochar. Thus, the optimum pyrolysis conditions are at 300°C and 20 min and the considered maximum biochar yield is 69.64 % by wt.

After obtaining the optimum, an experimental verification was conducted to evaluate if the actual yield has less than 10 % difference to its theoretical yield generated by Design Expert®. The obtained data mean is within the 95 % prediction interval and the percent difference between the actual and predicted mean was 1.53 %. Thus, the obtained and selected optimum conditions (300°C and 20 min holding time) from numerical optimization is acceptable for maximizing biochar production from MSW.

3.3. **Biochar Characteristics**

For the characterization of biochar, two biochar samples were tested. The first one was the biochar with the highest yield that was produced at 300°C, 20 min (MSWB300) while the other was the biochar with the lowest yield at 600°C, 120 min (MSWB600). MSWB300 has a dark brown to black color probably due to the presence of partially pyrolyzed components. Whereas MSWB600 is black in color and more brittle. Both samples have still visible glass and sand components since these particles were not decomposed during pyrolysis.

3.3.1. **Proximate Analysis**

Aside from determining the combustible properties of the material, its suitability as solid fuel can also be assessed through proximate analysis as shown in Table 1. Low moisture and hydrophobicity of biochar are some of the desired characteristics for better fuel performance. Since most biomass is hydrophilic due to high moisture content, pyrolysis process decreases the hydrophilicity of the biochar[29]. Increasing the temperature and holding time resulted to a much lower moisture content. Additionally, low moisture content is desirable since high moisture can decrease the heating value of the material and can result to problems on flame stability when used as solid fuel for energy production[23][20]. The VCM of biochar samples decreased from 48.8 % by wt to 20.36 % by wt when both parameters were increased. This is comparable to the study of Yuan et al.[14] wherein the VCM of biochar from MSW decreased from 74.0 % by wt to 27.7 % by wt from 300°C to 450°C, respectively. This is because at increasing temperatures and time, volatile matter contents are devolatilized and removed in gaseous form. The VCM of biochar at low temperature such as in MSWB300 is high since the sample has a large fraction of organic (woody) materials. These woody materials have high lignin content which can resist decomposition during pyrolysis at low temperature[30]. For fuel applications, high gaseous and smoke emission might occur upon combustion due to high VCM content such as in
MSWB300\textsuperscript{[28]}. As for the ash content, an increase in the temperature and holding time has increased the ash content of biochar from 27.6 \% by wt to 38.37 \% by wt. This result is expected since the volatile matter undergoes decomposition as pyrolysis conditions were increased leaving a high fraction of ash in the solid residue\textsuperscript{[10]}. Additionally, the ash contents of MSWB300 and MSWB600 are greater than that of MSW biochar in Yuan et al.\textsuperscript{[14]}, due to their non-combustible inorganic and glass components. An advantage of biochar with high ash is that it can be used to increase the pH of soil. This is because ash may contain basic compounds such as CaCO\textsubscript{3} and KHCO\textsubscript{3} which when applied to soil may decrease its acidity\textsuperscript{[31]}. In this study, MSWB600 has high ash content of about 38.37 \% which might be a potential substitute to other materials used to neutralize the soil. Lastly, increasing the pyrolysis conditions also increased the fixed carbon content of biochar from 23.6 \% by wt to 41.27 \% by wt. This is also due to the escape of volatile matter during pyrolysis at higher conditions, thus increasing the non-volatile constituents in the char including ash and fixed carbon\textsuperscript{[32]}. A high fraction of fixed carbon in the biochar implies a lower VCM content as observed in Table 1. Moreover, aromatic carbon in the char corresponds to its high amount of the fixed carbon produced at higher temperature\textsuperscript{[33]}. 

3.3.2. Elemental Composition

Pyrolysis resulted to a change in the elemental composition between the raw MSW and MSW-derived biochar. It leads to the formation of carbonaceous solid residue, thus increasing the C content in MSWB300 (51.02\%) than the raw MSW (36.89\%). According to Tag et al.\textsuperscript{[29]}, further increase in temperature and holding time results to an increase in C in biochar which was observed in this study. From 300°C and 20min holding time, \%C increased from 51.02\% to 55.54\% at 600°C and 120min. On the other hand, there was a loss in H and O during pyrolysis because of the bond breakage of the weak bonds in the biomass\textsuperscript{[34]}. Moreover, Della Rocca et al. as cited by Suman & Gautam\textsuperscript{[26]} stated that dehydration and decarboxylation occur at increasing temperature and holding time. The H decreased from 4.58 \% to 1.03 \%; whereas O decreased from 15.93 \% to 4.22 \% at increasing temperature and time. For the N content, the value decreased from 0.87\% to 0.84\% at increasing temperature and time probably due to further devolatilization of the components which may contain some N\textsuperscript{[29][35]}. For the S content of this study, no significant amount was detected similar to that of the raw MSW sample.

3.3.3. Higher Heating Value (HHV)

According to Sukiran et al.\textsuperscript{[6]}, one important fuel quality index is the heating value since it indicates the energy content of the material. MSWB300 and MSWB600 were found to have HHVs of about 15.82 MJ/kg and 13.03 MJ/kg, respectively. Based from the result, HHV decreased when the temperature and holding time were increased, probably because of the removal of volatile combustible component at higher temperature\textsuperscript{[32]}. Another reason is due to an increasing ash content of the biochar at an increasing temperature and holding time since HHV varies depending on the ash content of biochar. A high ash in the biochar reduces its energy content; thus, the HHV of carbonized substances is lower than the HHV of pure carbon material with graphitic structure\textsuperscript{[10]}. In the study of Yuan et al.\textsuperscript{[14]}, the HHV of MSW at 300°C is 27.72 MJ/kg. This is higher than that of the MSWB300 and MSWB600 due to the high ash content of the two biochars compared with that of the MSW from the mentioned study.

3.3.4. Surface Area

Residence time as well as pyrolysis temperature affects the characteristics of biochar such as porosity and surface area. Based from the result of the Nitrogen Sorption Analysis, MSWB300 is non-porous while MSWB600 is porous with a surface area of 95.4 m\textsuperscript{2}/g. According to Lu et al\textsuperscript{[36]}, increasing the holding time and temperature leads to pore size and surface area development. This is due to the devolatilization of volatile matter which leaves holes in the char structure, thus increasing porosity\textsuperscript{[37]}. Since MSWB300 has high VCM content compared to that of MSWB600, more volatile components were still in the char, hence, only few holes were formed as shown in Figure 1. Due to the high adsorptive capacity of MSWB600 which is then attributed to its high surface area and porosity\textsuperscript{[38]}, it can be used to treat wastewater through adsorption.
3.4. Energy Recovery and Classification of Biochar using van Krevelen Diagram

Energy recovery from the feedstock is an important factor in assessing the potential of MSW-derived biochar as solid fuel. The energy recovery based on biochar yield decreased from 76.37% to 32.75% when the temperature and time were increased from 300°C, 20 min to 600°C, 120 min, respectively. This is due to a decreasing biochar yield at higher temperatures since energy recovery is heavily influenced by the mass yield. Thus, MSW-derived biochar at the optimum conditions has greater energy recovery as well as mass yield. However, though MSWB300 has higher HHV and energy recovery, using it for energy production may result in emission of more gaseous substances since it still has high VCM content, thus, lower quality compared to that of MSWB600.

MSWB300 with higher calculated H/C and O/C ratios compared to MSWB600 is only comparable to lignite using van Krevelen diagram. This means that MSWB300 was not fully carbonized due to a lower C content compared to MSWB600. On the other hand, plotting both ratios for MSWB600 suggests that it is comparable to anthracite coal as shown in Figure 2. MSWB600 has better coal rank than MSWB300 due to its higher carbon content; thus, for a better quality of solid fuel in terms of its coal rank, MSW-derived biochar should be produced at higher pyrolysis conditions (600°C, 120 min). Using biochar at the mentioned conditions can produce energy without emitting too much gases because of its low VCM content; however, its energy recovery is lower.

4. Summary and Conclusion

This study explored the thermochemical conversion of municipal solid waste via pyrolysis to produce biochar, which is a potential alternative to fossil fuel. The effects of pyrolysis conditions including temperature and holding time on biochar yield were determined using factorial experiment. It was found out that both temperature and holding time have significant effects on the yield wherein increasing the extent of both parameters led to a decrease in biochar yield. Based from the optimization study,
maximum MSW-derived biochar yield (69.64 % by wt) can be produced at 300°C for 20 min. This value was considered as the maximum yield since further decrease on the temperature and holding time will not satisfy the range of operation for slow pyrolysis.

The characteristics obtained at optimum conditions indicate its potential as alternative fuel. The HHV of the optimum biochar is about 15.82 MJ/kg, which was found to be higher than raw MSW (14.42 MJ/kg). From the mass yield and HHV, the energy recovery was determined and the optimum biochar accounts to about 76.37 % energy recovery from the raw MSW. Furthermore, it was found out that the biochar produced at the optimum pyrolysis conditions is comparable to lignite while biochar produced at high temperature and holding time is comparable to anthracite coal. Based from its characteristics, biochar produced at lower temperature and holding time can be applied as solid fuel due to its high HHV and energy recovery; however, formation of smoke during combustion for energy production might be observed. On the other hand, a better quality of solid fuel close to anthracite coal with clean smoke upon combustion can be achieved at higher pyrolysis conditions. Moreover, biochar produced at extreme (high temperature and holding time) pyrolysis conditions has potential to treat contaminants in wastewater through adsorption based on the increase in surface area and can help in neutralization of soil.

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