

Optimal Condition of Torrefied Biomass Production With High Energy Yield

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Abstract

Abstract— This study aimed to produce the torrefied biomass with high energy density for the solid bio-fuel application. Biomass wastes; coffee ground residue, sawdust and corncob, were mixed at the fixed ratio of 4:3:3 by weight. Central composite design was applied for experimental design with two independent factors: temperature and time for torrefaction. The optimum condition of torrefaction was investigated by response surface methodology. The severity factor in the term of process variables was represented to justify the response as weight loss, heating value and energy yield. Increase of severity factor reduced the energy yield, increased the weight loss and heating value of torrefied biomass. Compared to the raw biomass waste, the heating value of torrefied mixed-biomass waste was improved about 29.51 to 61.02%. The heating value and weight loss in biomass slowly increased as the severity factor increased up to 6.90 and then quickly increased when severity factor over than 6.90, resulted to the decrease of O/C and H/C molar ratio. From the optimal condition with severity factor of 6.32 at about 254°C and 60 min, response in weight loss, heating value and energy yield, was 40.77%, 25.00 MJ/kg and 83.35 % and, respectively. This torrefied biomass will be further densified in the pellet form to meet the requirement of industrial sector.

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I. INTRODUCTION

One of effective energy renewable resource is lignocellulosic biomass which can be converted into heat and different fuel forms to meet the energy demand nowadays. Biomass fuel pellets are widely used for residential heating and thermal power generation in many countries. Biomass pellets can be used for burning or power generation because of its convenience and comfort. In addition, it has extremely high efficiency and environmental friendly characteristic. Considering the environmental factors, biomass wood pellets are preferable to coal for electricity generation because they burn cleanly. Biomass fuel densification process generally consists of drying unit, reduction unit and steam conditioning unit before the pelletization take place. After that, the

biomass pellets goes through the cooling unit to maintain its stability. However, the wood pellet has lower energy density and a higher moisture content than coal. Due to the biofuel pellets are produced from many different kinds of feedstock and cause it to have heating value and ash content differently. To solve this problem, torrefaction is applied before the densification step in order to enhance the quality of biofuel pellets. The torrefaction is conducted at the mild condition of a temperature range of 200-300°C for less than an hour [1]. Hydroxyl group and some light volatile are removed from the biomass structure during the thermal treatment cause more charring surface leading to more proportion of carbon content. Therefore, the torrefied biomass has high heating

value, volumetric energy density, consistency and water-resistance. Both chemical and physical characteristics of torrefied biomass are appropriated throughout the long distance transportation and storage. In addition, the size reduction of torrefied biomass before entering the pelletization process is made easier than of raw biomass. due to hemicellulose structure has been degraded during torrefaction progress. Hence, the torrefaction process is inserted between drying unit and size reduction unit before pelletization unit, called TOP process (torrefaction and pelletization process) [2]. The produced TOP pellet with high energy density and hydrophobic property was used instead coal in combined heat and power plant. The weight loss of biomass during torrefaction process depends on torrefaction condition, such as temperature, time and heating rate. Actually, fuel property of torrefied biomass is determined from heating value, proximate analysis and ultimate analysis. However, these properties vary with various feed characteristic and process factors. Consequently, pretreatment of biomass via torrefaction process is the key success of biofuel production for heating and power generation. According to the related reports on torrefaction process of various biomass wastes performing at different conditions. Shang L et al. [3] investigated the quality improvement of Scottish pine before pelletization. Torrefaction was carried out at 230, 250 and 270°C for an hour under nitrogen atmosphere. They found that the heating value of biofuel has been enhanced from 18.37 MJ/kg to 24.34 MJ/kg. Prins *et al.* [4] applied the torrefaction process for biomass pretreatment at temperature range of 200-300°C in the nitrogen atmosphere. It was found that mostly of volatile matter was evaporated into vapor during the temperature of 250-300°C. According to the same torrefaction, heating value of torrefied Albasia was lower than torrefied Acacia while the weight loss of Albasia was higher than Acacia. However, there was a few studies on the factors influence on the property of torrefied biomass. Wei-Hsin Chen *et al.* [5] selected 3 levels of

temperature; 220, 250 and 280°C in torrefaction process for 0.5, 1, 1.5 and 2 hours. It was found that torrefaction at a temperature of 280°C gave the torrefied wood with the higher heat value up to 140% of the starting wood. However, weight loss of wood was more than 50% when the torrefaction temperature and reaction time was higher than 250°C and one hour, respectively. Also, the advantage of torrefaction was reported that grinding of torrefied wood pass produced at 280°C was done easily. Consequently, energy consumption in this aspect was reduced significantly.

Different conditions were investigated upon the research purpose. The statistical experimental design techniques have been applied for experimental design, model building and problem analysis. It is useful for understanding the interactions among the parameters of two or more variables that have been optimized and searching for the optimum conditions. For instance, Chin, K L. *et al.* [6] explored the torrefaction experiment of three biomass material types; Acacia, Macaranga and Empty fruit branch. They used Design Expert 8.0.1 program and defined two independent variables that is temperature and time. Temperature range was around 200-300°C and time was in the range of 15-45 minutes. The response variable was heating value (HHV) of torrefied product. The relationship equation between each variable interaction was represented in the full quadratic equation based on ANOVA result. Predicted model gave the optimal conditions to get the maximum response. According to the studies of Young-Hun Kim *et al.* [7], torrefaction of Acacia and Albasia biomass was determined at the temperature range of 220-280°C for 20-80 minutes. The variables interactions and response surface methodology (RSM) were applied. The carbon content of torrefied biomass increased with the value of severity, Heating value of torrefied Acacia was in the range of 20.03-21.60 MJ/kg. The energy yield was increased from 5.09% to 13.62% as compared with raw biomass. However, torrefaction of biomass at the strong condition; high temperature for longer period, is not the preferable

condition [8]. Optimal parameter for torrefaction process of biomass fuel has been discussed in the terms of energy yield determining in both heating value and production yield of torrefied biomass on the dried basis. Lee, J W. *et al.* [8] applied Design Expert 8.0.1 for factorial design and optimization with response surface methodology of soft wood torrefaction. Totally 22 runs were designed with 2 dependent variables, temperature and time in the range of 220-280°C and 20-80 min, respectively. Severity factor was determined for optimal condition. Response variables were heating value (MJ/kg), weight loss (%) and energy density yield (%). After torrefaction, the heating value of biomass had been

announced from 19.31 to 22.12 MJ/kg. Increase of severity value to 6.12 made the weight loss and heating value slightly increased. After that, both terms and energy density yield slowly reduced.

This reports aimed to prepare the torrefied biomass with balancing both quality and quantity using Minitab 16 in CCD experimental design with two dependant variables; temperature and time in torrefaction. The responses were weight loss (%), heating value (MJ/kg) and energy yield (%). Predicted equation was proposed based on ANOVA result and the optimal condition was evaluated with response surface methodology.

factor

Table 1 Experimental conditions and values severity

| Run | Variables | | Coded level | | Severity factor (SF) |
|-----|-----------------------------|-----------------------------------|----------------|----------------|----------------------|
| | Time (min, X ₁) | Temperature (°C, X ₂) | X ₁ | X ₂ | |
| 1 | 20 | 240 | -1 | -1 | 5.42 |
| 2 | 20 | 320 | -1 | 1 | 7.78 |
| 3 | 60 | 240 | 1 | -1 | 5.90 |
| 4 | 60 | 320 | 1 | 1 | 8.26 |
| 5 | 40 | 240 | 0 | -1 | 5.72 |
| 6 | 40 | 320 | 0 | 1 | 8.08 |
| 7 | 20 | 280 | -1 | 0 | 6.60 |
| 8 | 60 | 280 | 1 | 0 | 7.08 |
| 9 | 40 | 280 | 0 | 0 | 6.90 |
| 10 | 40 | 280 | 0 | 0 | 6.90 |
| 11 | 40 | 280 | 0 | 0 | 6.90 |
| 12 | 40 | 280 | 0 | 0 | 6.90 |
| 13 | 40 | 280 | 0 | 0 | 6.90 |

II. EXPERIMENTAL

Biomass wastes; corn cob, ground coffee residue and sawdust were collected from the local sources. They were initially sun-dried in order to decrease humidity less than 10% by mass. The milled biomass samples were sieved to 100 mesh to guarantee its homogeneity.

A. Experimental Design

In the design of the torrefaction of mixed biomass, The Minitab program, version 16, was employed in order to find out response of each factor. There were two factors: time and temperature used in the torrefaction process. However, Central Composite

Design (CCD) was used in designing with full factorial design, $\alpha=1$ and the temperature range (X₁) of 240-320°C and time (X₂) of 20-60 minutes. There were three response variables: weight loss% (Y₁), heating value (Y₂) and energy yield% (Y₃). Equation (1)-(3) were used to evaluate the torrefaction effect, the weight loss, energy yield and severity factor (SF). Where W_i is sample weight before torrefaction, W_f is sample weight after torrefaction, E_f is heating value of torrefied sample, E_i is heating value of sample before torrefaction (dried basis), SF is severity, t is torrefaction time (min), T_H is torrefaction temperature (°C) and T_R is the reference temperature of 100°C.

$$\text{Weight loss (\%)} = (100\%) \frac{(W_i - W_f)}{W_i} \quad (1)$$

$$\text{Energy yield (\%)} = (100\%) \frac{(W_f E_f)}{(W_i E_i)} \quad (2)$$

$$\text{SF} = \log \left\{ t * \exp \left(\frac{(T_H - T_R)}{14.75} \right) \right\} \quad (3)$$

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{12} X_1 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \varepsilon \quad (4)$$

Therefore, 13 trials were performed as shown in Table 1, all response value for each run was recorded as the mean of triplicates. The polynomial regression equation was developed based on CCD in order to analyze factor interactions contributing to the regression model and to determine the optimum values. The ANOVA was obtained to correlate the dependent and response factors, Equation (4) was presented as the full quadratic for this relationship. Where Y is the response, β_0 and ε is the constant and the random error, respectively. X_1 and X_2 are the independent variable effects, X_{12} and X_{22} are the square effects. β_1 and β_2 are the linear coefficients; β_{12} is a cross product coefficients; β_{11} and β_{22} are the squared coefficient. The quality of the fit of the regression model was expressed with the coefficient of determinations (R^2 , R^2_{adj}) and statistical significance was checked by the F-test. Model terms were selected or rejected based on the probability value with 95% confident level. By using response surface methodology (RSM) technique, the 3D response surfaces were drawn to visualize the individual and interactive effects of the independent variables on each response. The optimum condition for the production of torrefied biomass was obtained, and three replicated runs at this condition were performed in order to check the validity of the predicted model.

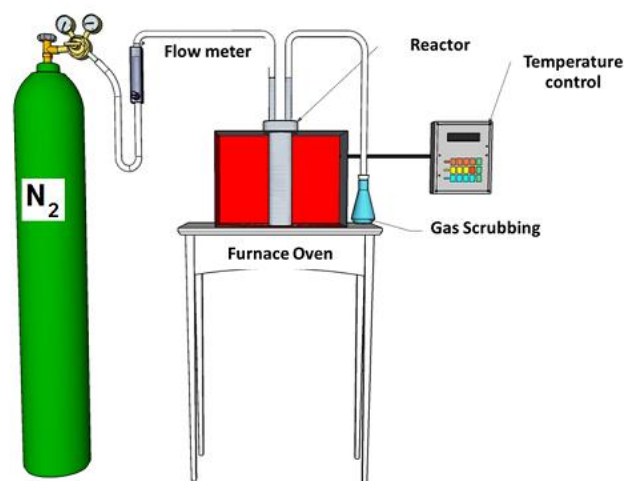


Figure 1 schematic setup of biomass torrefaction

B. Biomass Torrefaction

The stainless-steel reactor with a hollow cylindrical shape and one opened-side. The pipe mouth was covered with a screw lid having an inlet hole for the nitrogen flow and outlet hole for the hot vapor release. The reactor dimension was 27 cm-height and 5 cm-internal diameter. Industrial grade of nitrogen gas was supplied during torrefaction by the controllable flow-meter of Dwyer company. Torrefaction temperature was controlled by temperature controller linked to wall-thermocouples as shown in Fig. 1. The coffee ground residue, sawdust and corncob were mixed at the weight ratio of 4:3:3. The weighed sample of 70 g was put into the reactor, the torrefaction was carried out accordance with the experiment design (Table 1). Sample was heated from the room temperature at the target temperature with the heating rate of 10°C/min in the constant nitrogen atmosphere of 800 cm³/min. Hot vapor was trapped in the water bath before releasing to the atmosphere. After the end of operation, heating was switched off and left the reactor cooling down to the room temperature. Finally, the torrefied product was collected and weighed for calculating of the product yield (%) and weight loss (%). Then it was brought to heating value analysis using Bomb calorimeter analyzer in order to calculate the energy yield (%). All experimental data was analyzed for ANOVA result and predictive model including the response surface of each factor.

C. Analysis of raw biomass and torrefied biomass

The raw biomass and torrefied biomass were detected for the calorific value per mass by using Auto Bomb Calorimeter machine of Gallenkamp. Sample pellet of 1 g was placed in a crucible that is put inside of a reactor with high-pressure oxygen. The sample was connected to a fuse and electrical leads that would ignited the sample. Equation (5) was used for this calculation. Where C_v (J/g) is the calorific value of sample per unit mass, C_p (J/g.°C) is the heat capacity used in this standard test, ΔT (°C) is equal to the different of final temperature and initial temperature, C_w (J) is the heating value of tested wire, C_c (J) is the heating value of fire cotton, W_s is the sample weight (g).

$$\text{Calorific value } (C_v) = (C_p \Delta T - C_w - C_c) / W_s \quad (5)$$

A Thermo Gravimetric Analyzer (TGA 50) was employed in Thermogravimetric Experiments. Ground coffee residue, sawdust and corncob and torrefied mixed-biomass which obtained from each torrefaction condition were milled. Approximately 5 mg of sample was evenly distributed in platinum sample pan of 9.6 mm diameter. The measurements were carried out in 300 cm³/min high purity nitrogen gas flow. Each experiment was started with a 20 min purging period at room temperature, then the heating ramp of 15°C/min was programmed until 700°C. When this point is reached, flue gas was changed for oxygen for 10 min. Five experiments were carried out with each biomass at the same heating programs in

order to ensure its thermal degradation behavior.

Proximate analysis is a broad measurement to determine the moisture content, volatile matter content, fixed carbon content, and the ash content. Moisture was determined by using standard oven dry method. Equation (6) was applied for the moisture determination (%MC) based on the standard method as heating of 1 g biomass sample in a hot air oven to 105±5°C. Where W_1 is the weight of the crucible containing the air-dried sample (g), W_2 is the weight of the crucible containing oven dried sample (g) and W_3 is the weight of the air-dried sample taken (g). Determination of ash content (%AC) in all the samples was determined according to standard procedure, defining as the weight of the residue remained after complete burning of 1gm of the biomass at 575±25°C. Equation (7) was used for the calculation of ash content, where W_4 is the weight of the crucible containing the oven dried sample (g), W_5 is the weight of the crucible containing residue (g), W_6 is the weight of oven dried sample taken (g). Volatile matter was determined by using cylindrical crucible by heating the sample for 7 min at 925±50°C in muffle furnace. Volatile matter (% VM) was calculated from total weight loss minus loss due to moisture. Equation (8) was used for estimation of the content of fixed carbon as subtracting the sum of %AC, %VM and %MC from total of 100% composition. Equation (9)-(12) were used for the ultimate analysis in the terms of elemental content of carbon (%C), hydrogen (%H), oxygen (%O) and nitrogen (%N) [9], [10].

Table 2 proximate and ultimate analysis of biomass

| BIOMASS | Proximate analysis (%wt.) | | | | Ultimate analysis (%wt.) | | | | Heating value |
|---------------|---------------------------|--------|-------|-------|--------------------------|-------|--------|--------|---------------|
| | MC | VM | FC | AC | C | H | O | N | |
| Coffee ground | 11.822 | 79.217 | 2.108 | 6.852 | 37.387 | 5.021 | 38.348 | 19.244 | 19.811 |
| Sawdust | 11.176 | 88.338 | 0.292 | 0.194 | 40.380 | 5.492 | 42.138 | 11.991 | 18.415 |
| Corn cob | 10.969 | 82.906 | 4.844 | 1.282 | 40.807 | 5.392 | 40.936 | 12.865 | 16.387 |
| Mixed biomass | 12.408 | 84.458 | 1.516 | 1.618 | 39.394 | 5.315 | 40.663 | 14.324 | 17.517 |

Table 3 Experimental and predicted responses at the designed severity factors.

| Severity factor (SF) | Experimental Responses | | | Predicted Responses | | |
|----------------------|-----------------------------|--|-----------------------------|-----------------------------|--|-----------------------------|
| | Weight (Y ₁ , %) | Heating value (Y ₂ , MJ/kg) | Energy (Y ₃ , %) | Weight (Y ₁ , %) | Heating value (Y ₂ , MJ/kg) | Energy (Y ₃ , %) |
| 5.42 | 25.310 | 22.686 | 96.738 | 23.080 | 22.600 | 103.800 |
| 5.90 | 33.510 | 23.882 | 90.658 | 40.120 | 24.240 | 90.200 |
| 7.78 | 60.830 | 26.426 | 59.088 | 58.200 | 26.840 | 66.600 |

| | | | | | | |
|------|--------|--------|---------|--------|--------|--------|
| 8.26 | 61.860 | 27.550 | 59.984 | 75.240 | 28.480 | 53.000 |
| 6.60 | 26.380 | 24.414 | 102.614 | 40.640 | 24.720 | 85.200 |
| 7.08 | 56.550 | 26.992 | 66.957 | 57.680 | 26.360 | 71.600 |
| 5.72 | 22.010 | 22.876 | 101.848 | 31.600 | 23.420 | 97.000 |
| 8.08 | 63.600 | 28.212 | 58.619 | 66.720 | 27.660 | 59.800 |
| 6.90 | 45.090 | 25.313 | 79.351 | 49.160 | 25.540 | 78.400 |
| 6.90 | 49.880 | 27.695 | 79.241 | 49.160 | 25.540 | 78.400 |
| 6.90 | 53.440 | 25.256 | 67.136 | 49.160 | 25.540 | 78.400 |
| 6.90 | 48.160 | 26.146 | 77.374 | 49.160 | 25.540 | 78.400 |
| 6.90 | 43.760 | 24.845 | 79.770 | 49.160 | 25.540 | 78.400 |

III. RESULTS AND DISCUSSION

A. Properties of raw biomass, and torrefied biomass

At beginning, corncob, ground coffee residue and sawdust were tested for the thermal degradation as the temperature-time function setup illustrating in the dash line as shown in Fig. 2. The TG curves of coffee ground residue, sawdust and corncob are also presented. The TG curves represent the percentage mass loss of a sample based on its initial mass at the heating rate of 15°C/min. Thermal decomposition of these biomass samples had 3 periods of weight. It was found that the weight of the sample decreased slightly at the initial temperature between 100-120°C, which is the evaporation of moisture from biomass. Volatile matters began to be released at a temperature of 250°C and the removal of various volatile substances will be finished at a temperature of 700°C. The combustion in air atmosphere was maintained at this final temperature about 5 min. From the TG curves of biomass samples, it was found that corncob was more easily degraded at the the low temperature than the others. Coffee ground residue had the highest ash content left after combustion. The proximate analysis was analyzed in the term of moisture content (%MC), volatile matter (%VM), fixed carbon content (%FC) and ash content (%AC). Ultimate analysis was characterized for the elemental composition of the organic portion of samples presenting on a weight percentage.

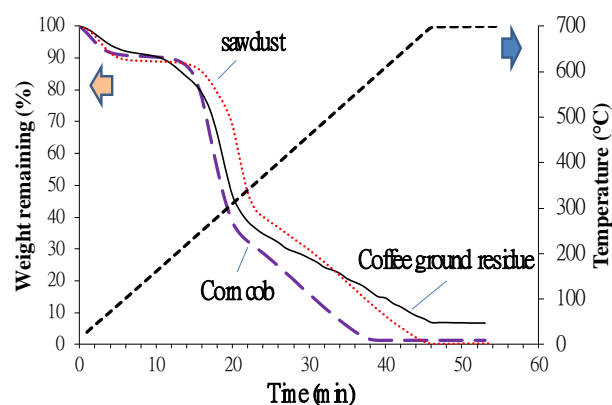


Figure 2 TG curves curves of the samples

From Table 2, it was found that each biomass sample and mixed-biomass contains high volatile matters, indicating the ability to ignite easily when used as fuel. Heating or calorific value of any fuel is the amount of the heat liberated by that under specific conditions of combustion. The heat value in a given fuel is mostly a function of the fuel's chemical composition. The higher fixed carbon content promotes the higher heating value. In contrast, the biomass with high moisture content and ash content will not have enough potential to be used as fuel because it affects the reduction of heat value of the fuel. The Coffee ground residue will have a maximum heat value of 19.811 MJ/kg while the mixed-biomass had 17.517 MJ/kg.

In addition, each biomass sample contains different weight percentage of organic elemental components consisting of carbon, oxygen, hydrogen and nitrogen. Biomass is the organic material contains mostly contains carbon, hydrogen and hydrogen. high oxygen content in the structure, causing that the fuel efficiency was reduced. Fuel potential can be estimated from the molar ration of H/C and as discussed in Van Krevelen diagram [1]. Coffee

ground residue, sawdust and corncob had the molar ratio of H/C of 1.635, 2.635 and 3.635 respectively. In addition, their O/C molar ratio was 0.752, 0.769 and 0.783 respectively. The heating value of the fuel will be increased by the smaller value of these ratio. Table 3 presents the response value from experiment and predict model. Before getting the model, experimental results were shown that weight loss percentage increased with the higher SF because more releasing of volatile matter was promoted at the higher temperature. Consequently, its heating value of charring biomass increased. However, the energy yield (%) was varied on both heating value and production yield of torrefied biomass on the dried basis. The heating value of torrefied mixed-biomass was in the range of 22.686 MJ/kg – 28.212 MJ/kg as shown in Table 3, the highest heating value of torrefied sample was obtained at the torrefaction at 320°C and 40 minutes.

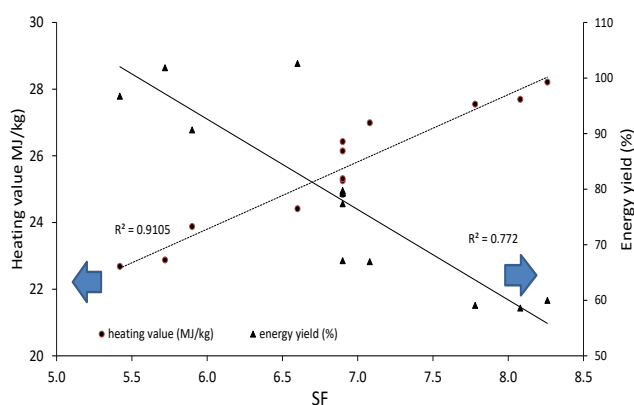


Figure 3 Heating value of torrefied mixed-biomass and energy yield from the different SF

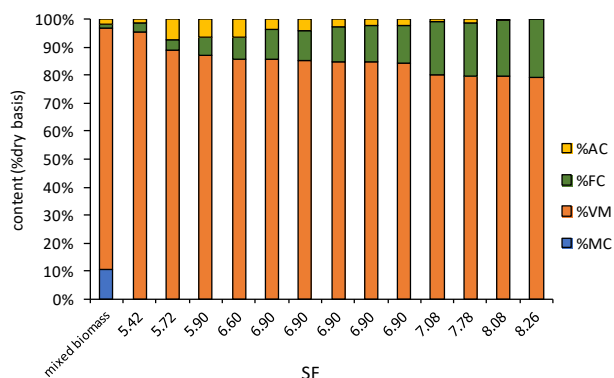


Figure 4 Content distribution of torrefied mixed-biomass

Heating value of torrefied biomass increases with

the SF value while the energy yield decreases (Fig. 3). As seen in Fig. 4, torrefied mixed-biomass had none moisture since the water was removed at the temperature of 100-105°C during the torrefaction. Also, more light organic and inorganic components were liberated and released; the torrefied biomass surface was getting higher charred so that the content of volatile matter and fixed carbon increased with higher SF. In addition, ash content was reduced after that. These results corresponded to the thermal degradation as described in Fig. 1. Minitab 16 was applied in experimental design based on CCD as mentioned in Table 1. The significant evaluation from the relationship between operating factors of torrefaction; temperature and time was conducted in order to investigate the optimum condition on production of torrefied biomass. The responses were determined in the term of weight loss (Y_1), heating value (Y_2) and energy yield (Y_3). These depended on the severity of each condition, so the term of severity factor (SF) was used in this discussion.

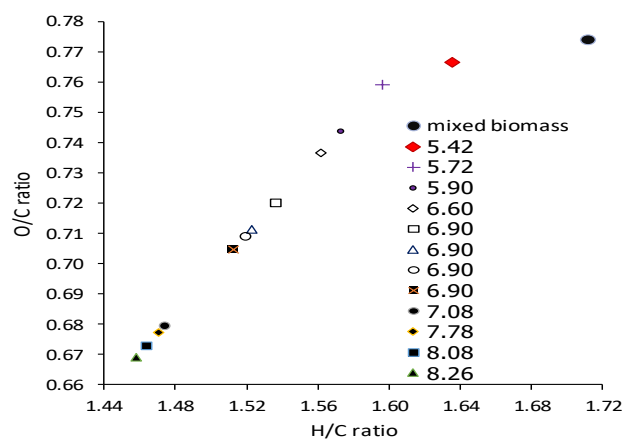


Figure 5 Fuel composition of torrefied mixed-biomass

Fig. 5 presents the elemental analysis of torrefied mixed-biomass in the term of molar ratio of H/C and O/C as the similar discussed in Van Krevelen diagram [1]. Mixed-biomass has the molar ratio of H/C and O/C about 1.712 and 0.774, respectively. It was discovered that these ratios reduced with higher SF value. Herein, the weight content of carbon and hydrogen induced while the weight content of oxygen and nitrogen reduced when the SF was getting increased. Therefore, the molar ratio of H/C

and O/C of the torrefied sample decreased getting to reveal the higher heating value under the stronger severity of torrefaction. This finding supported the positive effect of torrefaction on the biomass pretreatment before used as the potential fuel. However, the torrefaction condition has to be controlled at the optimum condition to balance among the heat consumption, product yield and product property. That is why the energy yield was presented in this work.

B. Statistically analysis and optimization

The relationship between responses (Y_1 , Y_2 and Y_3) and the independent variables (X_1 and X_2) in the form of empirical full quadratic equation for predicting the optimum condition was achieved through the CCD design. The model was achieved using ANOVA for the statistical significance of the main effects, interactions, coefficients and residues error. From the statistical analysis of variance (ANOVA) of the experimental data obtained ANOVA results as shown in Table 4. Based on the probability value with 95% confident level, the insignificant interaction terms ($P < 0.05$) in the full second-order polynomial was eliminated. The significance of the coefficient term was proved by the values of P and F, higher significance has the larger F-test value and smaller P values [8]. The quality of the fit of the regression model was expressed with the coefficient of determinations (R^2 , R^2_{adj}) and statistical significance was checked by the F-test. For a certain number of degrees of freedom in the model at the level of significance α , the F-value estimated using the experimental data corresponded to the total residual was greater than the tabular F-value distribution. So the proposed model was significant in the region studied. Also, the lack-of-fit is statistically insignificant to the pure error because the F-value estimated using the experimental data corresponded to the lack-of-fit was less than tabular F-value. After

considering the reliability of each significantly term (95% reliability or $P < 0.05$) resulting in a prediction equation of weight loss (Y_1), heating value (Y_2) and energy yield (Y_3) as presented in Eq (14)-(16). It was found that that R^2_{adj} was equal to 80.85%, 75.71% and 74.45% for these predictive equations respectively.

$$Y_1 = -90.80 + 0.426X_1 + 0.439X_2 \quad (14)$$

$$Y_2 = 9.06 + 0.041X_1 + 0.053X_2 \quad (15)$$

$$Y_3 = 222.2 - 0.340X_1 - 0.465X_2 \quad (16)$$

The 3D contour plots were obtained in order to consider the effecting variable and its mutual interaction which effecting to the response. These plots as shown in Fig. 6 provide a method to predict the best response range of biomass torrefaction for different values of the tested variables. It was found that increasing of temperature and time in torrefaction affect significantly on the increasing of the weighed loss percentage of biomass material and heating value of torrefied product. The maximum region of weight loss percentage was appeared when the temperature and time was more than 248°C and 30 min respectively. To produce the torrefied biomass with high heating value, the region of temperature and time in which higher than 350°C and 50 min respectively was suggested. This was caused by the liberation of organic and inorganic substance under high severity condition. The hydrocarbon compounds in the form of water and some light volatile matters were released from the structure resulting more charring surface. In the meantime, the energy yield of product compared to of precursor was reduced as described in Equation (2). Therefore, the energy yield response was getting decreased with longer time at higher temperature of torrefaction. The high response of energy yield was revealed at the temperature and time less than 238°C and 30 min respectively.

torrefied mixed biomass at the designed conditions

Table 4 Proximate analysis and ultimate analysis of

| |
|--|
| Weight loss (Y_1) $R^2 = 84.04\%$, $R^2_{adj} = 80.85\%$ |
|--|

| Source | Degree of freedom | Sum of squares | Mean squares | F-value | P-value |
|---|-------------------|----------------|--------------|---------|---------|
| Regression | 2 | 2112.36 | 1056.18 | 26.33 | 0.000 |
| Linear | 2 | 2112.36 | 1056.18 | 26.33 | 0.000 |
| Temperature | 1 | 1853.64 | 1853.64 | 46.21 | 0.000 |
| Time | 1 | 258.73 | 258.73 | 6.45 | 0.029 |
| Residual Error | 10 | 401.16 | 40.12 | | |
| Lack-of-Fit | 6 | 341.59 | 56.93 | 3.82 | 0.108 |
| Pure Error | 4 | 59.58 | 14.89 | | |
| Total | 12 | 2513.52 | | | |
| Heating value (Y₂) R² = 79.75%, R_{adj}² = 75.71% | | | | | |
| Source | Degree of freedom | Sum of squares | Mean squares | F-value | P-value |
| Regression | 2 | 31.067 | 15.5333 | 19.70 | 0.000 |
| Linear | 2 | 31.067 | 15.5333 | 19.70 | 0.000 |
| Temperature | 1 | 27.068 | 27.0683 | 34.32 | 0.000 |
| Time | 1 | 3.998 | 3.9984 | 5.07 | 0.048 |
| Residual Error | 10 | 7.886 | 0.7886 | | |
| Lack-of-Fit | 6 | 2.743 | 0.4572 | 0.36 | 0.876 |
| Pure Error | 4 | 5.143 | 1.2857 | | |
| Total | 12 | 38.953 | | | |
| Energy yield (Y₃) R² = 78.70%, R_{adj}² = 74.45% | | | | | |
| Source | Degree of freedom | Sum of squares | Mean squares | F-value | P-value |
| Regression | 2 | 2352.0 | 1176.00 | 18.48 | 0.000 |
| Linear | 2 | 2352.0 | 1176.00 | 18.48 | 0.000 |
| Temperature | 1 | 2074.0 | 2074.01 | 32.59 | 0.000 |
| Time | 1 | 278.0 | 278.00 | 4.37 | 0.063 |
| Residual Error | 10 | 636.4 | 63.64 | | |
| Lack-of-Fit | 6 | 521.7 | 86.94 | 3.03 | 0.151 |
| Pure Error | 4 | 114.8 | 28.69 | | |
| Total | 12 | 2988.4 | | | |

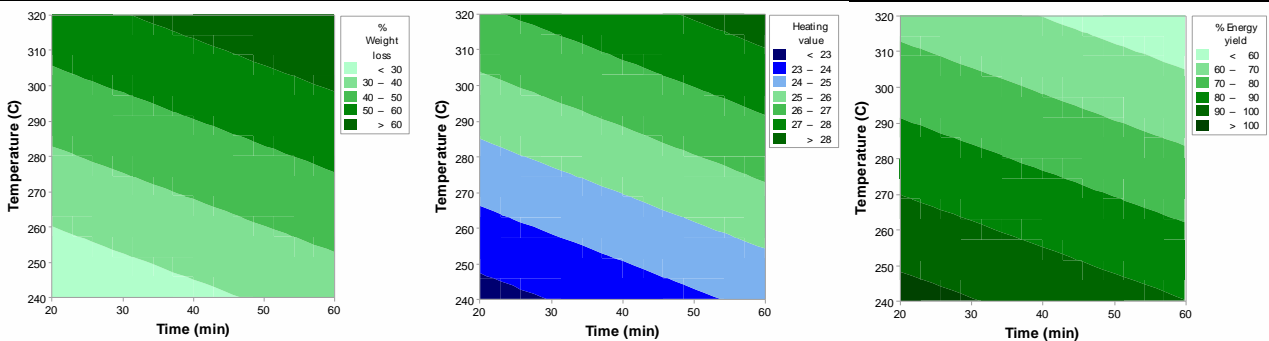


Figure 6 Contour plot effects with two variables varied within the experimental ranges

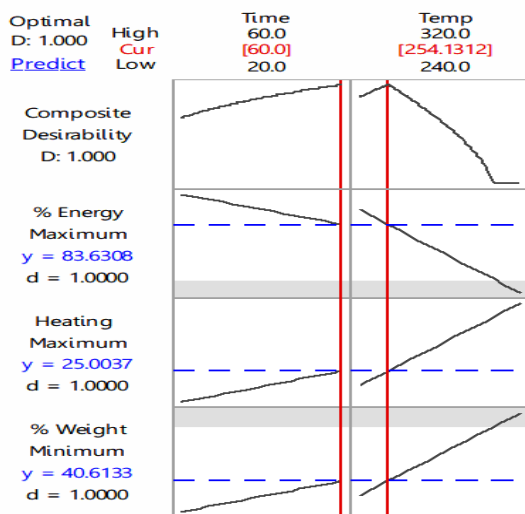


Figure 7 Optimal condition for the torrefaction

Thus, the optimum torrefaction condition for both quantity and quality with the highest composite desirability was evaluated by the response optimizer in MINITAB (version 16) software. In considering these three responses: heating value of torrefied mixed biomass (Y_1), weight loss of biomass (Y_2) and energy yield (Y_3); were optimized to get the value of highest, lowest and highest respectively. As seen in Figure 7, the optimal condition for biomass torrefaction was at 254°C and 60 min with severity factor of 6.32. The predicted weight loss percentage, heating value and energy yield of was 40.77%, 25 MJ/kg and 83.35% respectively. To test the validity of those predicted model, the replicated experimental

three runs at this optimal condition were conducted. It was discovered that the torrefied mixed-biomass had the average weight loss percentage heating value and energy yield of 41.32%, 24.75 MJ/kg and 85.74% respectively. These experimental values were in good agreement with the predicted values showing relatively small errors as seen in Table 5. Therefore, the RSM was effective and reliable for optimizing the production condition of torrefied biomass with high energy yield based on the untreated biomass. In addition to, the torrefied product producing at this optimal condition had volatile matters, fixed carbon and ash content of 83.421%, 15.254% and 1.325% respectively. According to ultimate analysis, it contained carbon, hydrogen, oxygen and nitrogen of 47.673%, 5.963%, 40.346% and 2.016% respectively. This torrefied product held the molar ratio of H/C and O/C at 1.502 and 0.698 respectively.

IV. CONCLUSIONS

Three kinds of biomass residue, ground coffee residue, sawdust and corncob; were treated with torrefaction process. The effects of process variables of torried product were determined by response surface methodology (Minitab16). ANOVA indicated that the proposed regression model of each response; weight loss, heating value and energy yield; based on Central-Composite Design had agreed with the experimental case with R^2 and R^2_{adj} correlation coefficients. Severity factor (SF) was used as the indication of the severity of torrefaction. The optimum condition balancing both quality and quantity for biomass torrefaction was 254°C and 60 minutes. There were 3 predictive response values as follows: 40.77% of weight loss, 25.00 MJ/kg of torrefied product and 83.35% of productive energy yield respectively. From the validity tests, these response values were 41.32 %, 24.75 MJ/kg and 85.74% respectively. The heating value of torried product was 141.29% of the original material, also contained lower molar ratios of H/C and O/C at 1.502 and 0.698 respectively. These findings have supported the further research on production of terrified biomass

pellets with high energy density.

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V. REFERENCES

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