Prediction Method for Torrefied Rice Husk Based on Gray-scale Analysis

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ABSTRACT: Torrefaction pretreatment has recently gained attention for the potential improvement in biomass properties. Otherwise, visible image-processing technology for analyzing properties of torrefied biomass was evaluated for possible use in the future online process control. In this study, torrefied rice husk from different torrefaction temperatures (180–330 °C) was obtained. After torrefaction, the biochar was characterized to determine the effects of torrefaction temperature on the properties, including the proximate analysis, solid yield (SY), and higher heating values. In addition, the color values, including red-green-blue (RGB) values, and grayscale (GS) of torrefied rice husk, were measured. The results show that the fixed carbon and ash increased from 17.39 to 35.13 and 7.06 to 38.41%, respectively, while volatile matters decreased from 71.47% to a minimum of 22.89% with the increase of torrefaction temperature from 105 to 330 °C. The SY remained higher than 46% even at the most severe torrefaction condition because of the high ash content and high remaining lignin. Moreover, the higher heating values of torrefied rice husk were increased from 14.80 to 17.82 MJ/kg when increased the pretreatment temperature. RGB values were decreased with the increase of torrefaction temperature. The GS analysis results show that the color of torrefied rice husk changed from yellow to brown at light torrefaction and black at severe torrefaction. GS of torrefied rice husk shows a good correlation (R = 0.9999) with torrefaction temperature. Prediction equations with higher fitting degree between GS and proximate analysis (R² > 0.9900), high heat values (R² = 0.9999), and SY (R² = 0.9979), which are developed to reflect the changing characteristics of torrefied rice husk. The results show that the prediction method based on GS is a promising technology to measure the properties of torrefied rice husk.

1. INTRODUCTION

Biomass is considered as an environmental friendly fuel by producing less greenhouse gas compared to fossil fuel.1 Raw biomass is characterized by high moisture and oxygen content, low energy, and the fibrous nature, causing the poor grindability and hygroscopic nature.2–5 These limitations make it complicated to be used on a large scale, enormously affecting the logistics and final energy performance. Therefore, in order to defeat these defects, pretreatment technologies are needed to make biomass appropriate for energy applications. Torrefaction, also known as mild pyrolysis and low-temperature thermal pretreatment, is carried out in an inert environment at 200–300 °C, with a residence time from a couple of minutes to several hours.6–10 During the thermal degradation process, cellulose, hemicellulose, and lignin, three major components of biomass, undergo different reactions, leading to a three-stage reaction: moisture removal, main decomposition, and formation of fixed-carbon.11 During the torrefaction, cellulose is slightly degraded, hemicellulose mostly decomposed while most lignin remains, producing solid bio-char, liquid bio-oil, and combustible gas, which can meet different energy needs. With the oxygen content departing as moisture and light matter volatiling, the amount of functional groups containing oxygen is reduced.12 However, the torrefaction characteristics and properties such as high heat values (HHVs) and solid yield (SY) remain unknown until complicated testing techniques are used to examine the torrefied biomass. In the past, numerous correlations regarding proximate, ultimate, or near-infrared reflectance spectroscopy analysis have been developed to predict the characteristics of raw and torrefied biomass,13–16 but these correlations were specifically developed to predict the HHVs of biomass, while other properties, such as the SY, might not show great correlation with the aforementioned analysis.17 Moreover, the proximate, ultimate, and NIRs analysis would take several hours to provide the measurement results, time-consuming, and costly. Therefore, developing other more accurate, faster, and higher-efficiency prediction methods will be the research trend in the coming future.

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Color values including red (R), green (G), and blue (B) value are the trichromatic colors and primary compositions of an image. After torrefaction, the color of biomass was changed from yellow to brown or black, which could be matched with the color values of torrefied biomass. Different ratios of the R, G, and B value could present torrefied biomass under different conditions with different properties. However, each pixel of picture might have more than 16 million (255 x 255 x 255) color schemes which make it impossible to analyze the correlation between the red-green-blue (RGB) values and characteristics of torrefied biomass. For example, Sarrafzadeh et al. applied a RGB color analysis to measure the cell concentration of three microalae and reported that the RGB color analysis showed poorer prediction than gray analysis.

Grayscale (GS) is the color value of a sample pixel representing only an amount of light, that is, it carries only intensity information. GS is defined to be a method that uses black as the basis color and different saturation to display the image. There would be no more than 255 GS values to predict the properties of torrefied biomass. Wang conducted an experiment on the biochar absorption characteristics based on GS analysis and reported that there was a strong positive correlation between adsorption characteristic and GS of biochar from the continuous pyrolysis reactor. Lindström et al. reported that visible and near-infrared imaging techniques for analyzing characteristics of torrefied biomass would be a promising online detective technology in future. With the application of GS analysis, online prediction of the properties of torrefied biomass would be realized.

To author’s best knowledge, there is limited publication on color values analysis of torrefied biomass and lack of such a study on developing a prediction method based on GS for torrefied biomass properties. In this study, the proximate analysis, HHVs, and SY of torrefied rice husk obtained from the fixed bed reactor are examined first. Then, digital image processing (RGB values analysis) and GS analysis of torrefied rice husk are analyzed for the first time. We explore the color value analysis method and evaluation equations for the quantification of the proximate analysis, HHVs, and yields of torrefied rice husk. This work would provide detail information of torrefied rice husk and develop a simple and inexpensive online measurement method in predicting the properties of torrefied rice husk.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Materials. Rice husk from Meizhou, China, was used as the feedstock for this study. The test code use RH and TRH as raw rice husk and torrefied rice husk, respectively. Before experiments, raw biomass was ground into pulverized particles by a mill. Then, the powders were shifted by a sieve to control the particle size to be smaller than 20 meshes. The sieved biomasses were dried in a blast drying oven at the temperature of 105 °C for 12 h to provide a basis for torrefaction experiment. Proximate analysis of rice husk shows that moisture, volatile matter (VM), fixed-carbon, and ash content were 4.07, 71.47, 7.06, and 17.39, respectively. The high heat value (HHVwb) of rice husk is 14.82 MJ/kg, which is in the wet base.

2.2. Torrefaction Procedure. Figure 1 shows the schematic diagram of torrefaction experiment, while Figure 1b is the digital picture of torrefied rice husk. The torrefaction device is a fixed bed reactor consisting of a quartz tube with an outside diameter of 38 mm and a length of 1200 mm. In each run, the pulverized powder with the total mass of 20 g (±1%) was first placed in the middle of the quartz tube, and then nitrogen gas (99.99%, purity) was purged through the tube at a flowrate of 150 mL/min (25 °C) to provide an oxygen-free atmosphere and remove volatile products from the tube during torrefaction. Then, the reactor was heated to the desired temperature (180–330 °C) with a difference of 30 °C with the same residence time of 20 min and the heating rate of 10 °C/min. After reaching the target temperature, started the stopwatch, and when it reached the target residence time, took out the sample to cool down in the air with nitrogen continuously purging through the tube. The torrefaction experiment under any given conditions was carried out triple to minimize the relative errors.

2.3. Properties of Torrefied Rice Husk. After torrefaction, the proximate analysis (ISO/DIS 17246), SY (eq 1), and HHVs (ASTM D5865-2007a) analysis were conducted to investigate the properties of the torrefied biomass. Furthermore, the enhancement factor (EF) (eq 2) of HHV and energy yield (EY) (eq 3) were analyzed in order to reflect the changes of energy more intuitively.

\[ SY = \frac{\text{mass}_{\text{TRH}}}{\text{mass}_{\text{RH}}} \times 100\% \]  

(1)

where \( \text{mass}_{\text{TRH}} \) and \( \text{mass}_{\text{RH}} \) were the remaining mass of torrefied rice husk and raw rice husk, respectively.

\[ EF = \frac{\text{HHV}_{\text{TRH}}}{\text{HHV}_{\text{RH}}} \]  

(2)

where \( \text{HHV}_{\text{TRH}} \) and \( \text{HHV}_{\text{RH}} \) were the HHVs of torrefied rice husk and raw rice husk, respectively.

\[ EY = SY \times EF \]  

(3)

2.4. Scanned Image Processing and Color Value Analysis. Torrefied biomasses were first scanned by a scanner
light matters in raw biomass. The increase in HHVs was ascribed to the removal of moisture and the increase of FC leads to the growth of HHVs. In addition, the great effects of torrefaction temperature, and FC, which has the greatest influence on the total energy, increased obviously. Therefore, with the increase of carbonization temperature, the great increase of FC leads to the growth of HHVs. In addition, the increase in HHVs was ascribed to the removal of moisture and light matters in raw biomass. Specifically, in the torrefaction process, the degradation of fiber contributes to the removal of oxygen and increment of carbon, resulting in the enhancement of HHVs. The SY of TRH deceased from 94.31 ± 2.57% to a minimum of 46.20 ± 1.86% (wt) when increased the torrefaction severity. Moreover, the SY remained higher than 46% even at the most severe torrefaction condition (330 °C) because of the high ash content in the rice husk feedstock.

Table 1. Proximate Analysis of Torrefied Rice Husk

| Temperature, °C | Proximate Analysis (wt %) | SY, % | HHVs, MJ/kg |
|-----------------|--------------------------|-------|-------------|
| 180             | 3.31                     | 61.29 | 17.29       | 94.31 | 14.99 |
| 210             | 3.15                     | 54.85 | 21.36       | 79.40 | 16.18 |
| 240             | 3.25                     | 40.50 | 26.64       | 62.61 | 17.35 |
| 270             | 3.31                     | 29.38 | 31.50       | 52.15 | 17.65 |
| 300             | 3.93                     | 26.51 | 32.76       | 49.15 | 17.72 |
| 330             | 3.56                     | 22.89 | 35.13       | 46.20 | 17.82 |

Though the SY decreased from 100 to 55.54% with the increase of torrefaction temperature, the SY was greater than the mass yield—an effect which became more remarkable for higher temperature pretreatment, and this shows the fact that the enhanced HHVs of torrefied biomass cannot keep up with the weight loss; thus leading to decreased total energy of biomass as the torrefaction temperature rose.

3.2. Color Values Analysis

3.2.1. Color Value Changes during Torrefaction. Table 2 shows the R, G, and B value and GS of RH and TRH. With the presentation of Figure 1b and the results obtained from RGB analysis for all samples, it shows a significant color variation with torrefaction temperature. The R, G, and B values were decreased with the increase of torrefaction temperature.

TRH with different properties obtained in different torrefaction conditions was finally characterized by different GS, as shown in Figure 3. The GS first decreased fast and then slowly with the increase of torrefaction temperature, which indicated that the color changing during torrefaction was more obvious than other higher temperature thermal conversion process, such as pyrolysis and gasification. The GS analysis shows that torrefied rice husk changed from yellow to brown at light torrefaction and black at severe torrefaction. The increase in darkness of torrefied rice husk could be the result of a nonenzymatic reaction between reducing sugar and amino acid in the thermal degradation process. The changes in color could reflect the changing characteristics of torrefied rice husk.

Equation 5 is the regression analysis result between GS and temperature. The fitting coefficient R² is 0.9998, which means that the GS of torrefied rice husk is closely related to the torrefaction temperature.

\[
GS = -398.62 + 13.92 \times T - 0.12 \times T^2 \\
+ 3.69 \times 10^{-4} \times T^3 - 4.10 \times 10^{-7} \times T^4,
\]

\[
R^2 = 0.9998
\]
correlation analysis was conducted between GS, volatile, FC, and ash. Their experiment values and fitting evolutions are shown in Figure 4a–c. As shown, they all change dramatically before 60 with the increase of GS, while then changed slowly, especially the curve of ASH, which almost leveled off. The changing curves of proximate analysis values all conform to the ExpAssoc model in the Origin Basic Function category.

Equations 6–8 were the corresponding regression relations. It can be seen that FC has the highest prediction accuracy, ASH takes second place, and VM has the lowest, but the fitting coefficients $R^2$ were all higher than 0.9900, which mean the gray value can explain the change of proximate analysis value to the extent of more than 99%. Thus, the ExpAssoc model can accurately predict the corresponding proximate analysis results, according to the gray value of torrefied rice husk after torrefaction or during torrefaction, which could be conveniently obtained within couple of minutes with the help of this developed prediction methods.

$$ \text{VM} = -57.133.00 - 57.172.25 \times (1 - \exp(-\text{GS}/4.05)) + 44.84 \times (1 - \exp(-\text{GS}/132.38)), \quad R^2 = 0.9978 $$

$$ \text{FC} = 2287.13 - 2258.23 \times (1 - \exp(-\text{GS}/5.57)) - 13800.49 \times (1 - \exp(-\text{GS}/107.142.50)), \quad R^2 = 0.9985 $$
ASH = 641.17 – 51.66 × (1 – exp(−GS/19.53))
− 572.34 × (1 – exp(−GS/7.66)),  \( R^2 = 0.9981 \)

(8)

3.2.3. HHVs Prediction. The use of biomass as a fuel in thermal applications requires knowledge of its higher heating values, but the determination of HHVs used to be time-consuming and expensive, so it is eager to find out a more economical and efficient prediction method. As analyzed above, both higher heating values and GS have a close relationship with torrefaction temperature, therefore, it is feasible to predict HHVs by GS. According to the experiment values of HHVs and GS, correlation analysis was conducted by Origin 9.1, and it can be found that their optimal fitting model conform to Boltzmann in Origin Basic Function category (Figure 5 and eq 9). HHVs closely corrected with GS of the torrefied rice husk with a strong unlinear correlation, whose fitting coefficient \( R^2 \) was 0.9999. Therefore, the effects of HHVs of biochar samples could be perfectly predicted by GS, which is cheap and convenient.

\[
\text{HHV} = 14.80 + (18.45 - 14.80) \\
/ (1 + \exp((\text{GS} - 50.15)/13.93)), \quad R^2 = 0.9999
\]

(9)

3.2.4. SY and Thermal Behavior Prediction. The values of SY changed with the increase of GS are shown in Figure 6, which climbed up dramatically before the GS value of 100, and then kept steady almost. The model fits into Asymptotic1 in the Exponential category, and the corresponding fitting regression analysis equation is shown as eq 10, and the fitting coefficient \( R^2 \) was 0.9979. The color values were closely relative to the SY of torrefied rice husk. That is, gray values could be explained the changes of SY in the sample biochar more than 99%. Therefore, by image recognition technology and with the help of the related equations, GS of torrefied rice husk could be obtained and then used to be predicted the values of SY, which is convenient and of high accuracy.

\[
\text{SY} = 100.20 - 159.25 \times 0.96^\text{GS}, \quad R^2 = 0.9979
\]

(10)

4. CONCLUSIONS

In this paper, a prediction method for the properties of torrefied biomass based on GS was developed. It was found that the higher heating values of torrefied rice husk were increased with the increase of torrefaction temperature, while the SY showed the opposite trend. The regression equations with a fitting degree higher than 0.99 were obtained between the GS value and proximate analysis, HHVs, and SY. The results obtained from this study suggest that GS analysis has strong potential to be developed into a promising approach for rapid quantification of torrefied biomass properties.

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Notes
The authors declare no competing financial interest.

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