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Predictions of biochar production and torrefaction performance from sugarcane bagasse using interpolation and regression analysis

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Abstract

This study focuses on the biochar formation and torrefaction performance of sugarcane bagasse, and they are predicted using the bilinear interpolation (BLI), inverse distance weighting (IDW) interpolation, and regression analysis. It is found that the biomass torrefied at 275 °C for 60 min or at 300 °C for 30 min or longer is appropriate to produce biochar as alternative fuel to coal with low carbon footprint, but the energy yield from the torrefaction at 300 °C is too low. From the biochar yield, enhancement factor of HHV, and energy yield, the results suggest that the three methods are all feasible for predicting the performance, especially for the enhancement factor. The power parameter of unity in the IDW method provides the best predictions and the error is below 5 %. The second order in regression analysis gives a more reasonable approach than the first order, and is recommended for the predictions.

Keywords: Torrefaction and biochar; Sugarcane bagasse; Bilinear interpolation; Inverse distance weighting (IDW); Regression analysis.

1. Introduction

Solid biomass can be considered as a potential alternative fuel to coal. In recent years, the research of torrefaction, a kind of mild pyrolysis which is operated at a temperature range of 200-300 °C, for producing biochar increases drastically (Bach et al., 2016; Chen et al., 2016; Rousset et al., 2011a). Solid (or biochar) yield, higher heating value (HHV) or its enhancement factor (or densification factor), and energy yield are three crucial indexes to indicate torrefaction performance. The higher the weight loss or the lower the solid yield, the higher the torrefaction severity. Three different torrefaction extents based on pretreatment temperature, including light torrefaction (200-235 °C), mild torrefaction (235-275 °C), and serve torrefaction (275-300 °C) (Chen & Kuo, 2010), have been classified to identify the impact of the pretreatment on hemicellulose, cellulose, and lignin (Chen et al., 2015c).

Though a higher torrefaction degree or severity is able to produce biochar with higher calorific value, both the solid (or biochar) yield and energy yield are lowered. Accordingly, seeking an appropriate torrefaction operation for producing required biochar fuels applied in industry is a desired goal. Torrefaction temperature and duration (or holding time) are two most common and important operating parameters to determine torrefaction severity and thereby products (Rousset et al., 2011b). Lee et al. (Lee & Lee, 2014) employed a gain and loss method to optimize torrefaction conditions which were determined from the intersection of the regression curves of calorific value and biomass weight versus severity factor which integrated torrefaction temperature and duration. Though the range of optimized severity factors was narrow, these factors were inherently dominated by biomass species used. Standberg et al. (Strandberg et al., 2015) torrefied Norway spruce in a continuous rotary drum reactor and evaluated the influence of temperature and duration on torrefied biomass using multiple linear regression. They found that solid products with similar properties could be obtained from different combinations of the temperature and duration in certain areas, but the two factors were not totally interchangeable. Wannapeera et al. (Wannapeera & Worasuwannarak, 2015) focused on the torrefaction of leucaena at the same torrefaction solid yields (60 wt%, 70 wt%, and 80 wt%) but at different combinations of torrefaction temperature and duration. They found that the elemental compositions of the torrefied biomass at the solid yield of 80 wt% were not affected by the combinations. On the other hand, at the solid yield of 60 wt%, the carbon content of the torrefied leucaena increased with rising temperature whereas the oxygen content decreased.

In addition to lignocellulosic biomass, torrefaction of microalgae residues has also received some attention lately. Chen et al. (Chen et al., 2015a) utilized contour maps to investigate the torrefaction characteristics and energy utilization of a microalga residue at various combinations of temperature and duration, and found that the torrefaction temperature had a trend to linearly decrease with increasing duration along the contour lines of solid yield. Another analysis (Chen et al., 2015d) further suggested that, at a given energy yield, a microalga residue torrefied at a lower temperature accompanied by a longer duration produced a biochar fuel with higher energy densification and lower solid yield, thereby rendering better torrefaction quality. On the other hand, a higher efficiency of energy utilization for upgrading the biomass could be achieved at a higher temperature along with a shorter duration. Consequently, the optimization of torrefaction operation depended on the requirement of energy densification of biochar fuel or energy utilization on the feedstock.

The literature reviewed above clearly suggests that the combination of torrefaction temperature and duration at a given biochar yield, calorific value, or energy yield plays a prominent role on torrefaction control, fuel properties, and energy utilization for upgrading biomass. With a desired solid or biochar yield, calorific value, or energy yield, how to combine the aforementioned two factors to hit the target is a crucial process. In the present study, three different methods, consisting of two interpolation means and a regression analysis, in terms of an operating matrix will be applied to predict the torrefaction performance. The relative errors between experimental measurements and numerical estimations will be evaluated, and appropriate methods will be recommended. The obtained results are able to provide useful tools to find out the appropriate operating conditions for gaining desired biochar.

2. Methods

2.1. Material

The feedstock used in experiments was sugarcane bagasse, which was the solid residue of sugar production from Taiwan Sugar Corporation in Tainan, Taiwan. Prior to carrying out torrefaction experiments, the bagasse was washed thoroughly with tap water until the effluent was clean and colorless. Then, the biomass was dried in an oven at 105 °C for 24 h to remove the water contained in the biomass. Subsequently, the dehydrated bagasse was comminuted by a shredder and sieved by 40 mesh and 100 mesh screens to produce feedstock particles with sizes between 0.149 mm and 0.42 mm. The powder was then collected and stored in sealed plastic bags and placed in a desiccator.

2.2. Experimental apparatus and procedure

The torrefaction system included a steel cylinder, a rotameter, a glass tube, a tube furnace, and a gas treatment unit. Nitrogen (99.99 vol%) was used as a carrier gas which was stored in the cylinder, and its flow rate was controlled by the rotameter. To ascertain the flow rate of the carrier gas, the rotameter was calibrated by a flow calibrator (Gillan-Stander Flow Cell-P/N 800266-1). The sample was loaded in the glass tube (32 mm i.d.) and the tube was placed in the furnace for carrying out torrefaction experiments. The torrefaction temperature was detected by a K-type thermocouple and controlled by a power controller installed in the furnace. The gas treatment unit was made up of two conical flasks in series.

In each experiment, 5 g of sugarcane bagasse was loaded in the glass tube. After the furnace reached the desired torrefaction temperature, the tube was placed in the furnace and nitrogen at a flow rate of 100 mL min^{-1} (25 °C) was blown into the tube to sweep the sample. The effluent, consisting of the carrier gas and vapors, was cleaned in the two conical flasks through a two-stage washing to avoid odor in the laboratory during the experiment. After the holding time reached the assigned duration, the tube was taken out from the furnace and the carrier gas kept sweeping the torrefied biomass in the tube for 15 min until the room temperature was achieved. After that, the residual solid was collected in sealed plastic bags and stored in a desiccator at room temperature for further analysis. In the present study, five torrefaction temperatures of 200, 225, 250, 275, and 300 °C accompanied by four durations of 15, 30, 45, and 60 min were carried out to form an experimental matrix. The torrefaction temperature covered the light, mild, and severe torrefaction (Chen et al., 2015a). Each experiment at the same operating conditions was performed twice to ensure the reproducibility of torrefaction where the difference was controlled within 5 %.

2.3. Analysis

To figure out the basic properties of the adopted sugarcane bagasse and the impact of torrefaction on the biomass, a number of analyses were carried out. The proximate analysis was performed in accordance with the standard procedure of American Society for Testing and Materials (ASTM), as described in the literature (Chen et al., 2015d). The elemental analysis was performed using an elemental analyzer (PerkinElmer 2400 Series II CHNS/O Elemental Analyzer) to measure the weight percentages of C, H, and N in the biomass, while the weight percentage of O was obtained by difference (i.e., O = 100-C–H–N). Normally, the sulfur content in biomass is very low so it was not measured in this study. In the fiber analysis, hemicellulose, cellulose, and lignin were measured following the method adopted in a previous study (Chen et al., 2012b). The higher heating values (HHVs) of the raw and torrefied samples were gauged by a bomb calorimeter (IKA C5000). The elemental analyzer and bomb calorimeter were calibrated periodically to ascertain the analysis quality.

The basic properties of the biomass include proximate, ultimate (or elemental), fiber, and calorific analyses. The analyses suggest that the values of volatile matter, fixed carbon, moisture, and ash are 78.74, 17.33, 1.41, and 2.52 wt%, respectively. The contents of C, H, N, and O (by difference) are 40.00, 6.74, 0.72, and 52.54 wt% (dry-ash-free), respectively. The percentages of hemicellulos, cellulose, lignin, and others in the raw biomass are 30.82, 41.32, 10.02, and 17.82 wt%, respectively. The HHV of the biomass is 15.95 MJ kg^{-1}. It can be seen that cellulose accounts for the largest portion (=41.32 wt%) in the bagasse and its HHV is 15.95 MJ kg^{-1}, which is located at the normal range of HHV of raw biomass (=15-25 MJ kg^{-1}) (Chen et al., 2015c).

2.4. Interpolation

One of the main purposes of interpolation is to smoothen images when they are enlarged or narrowed (Yang et al., 2017). Meanwhile, the numerical interpolation can be employed to produce a contour map for predicting solid and energy yields at various combinations of torrefaction temperature and time (Chen et al., 2015a; Chen et al., 2015d). Several interpolation methods such as Thiessen Polygon (Mu, 2009), fixed radius for local averaging (Turau, 1991), splines (Yang et al., 2015), Kriging (Khankham et al., 2015), bilinear interpolation (BLI) (Mastyło, 2013), and inverse distance weighted (IDW) (Lu & Wong, 2008) have been developed. In this study, the BLI and IDW methods will be adopted to predict three important torrefaction indicators, consisting of biochar yield, enhancement factor of HHV, and energy yield, due to their simpler algorithms and operations.

In the BLI method, predicted values can be obtained fast and conveniently through a three-step linear interpolation. It has been used in computer graphics to compute intermediate values on a continuous surface (e.g., GIS) (Mentis et al., 2015). Recent research using BLI emphasized on proving bilinear interpolation theorems to the setting of Calderon-Lozanovskii spaces (Mastyło, 2013). Alternatively, the IDW method has been widely used in image processing such as fast image interpolation and hydrogeological structure in rock mass (Jing & Wu, 2013; Mito et al., 2011). Recently, the IDW has also been applied in the coastal water pollution source models (Zhou et al., 2007). While applying the IDW method, each measurement assigned to an unknown point is calculated with a weighted average of the measurements at known points. Accordingly, the farther the distant of a known point to the unknown one, the less the influence of the former to the latter (de Mesnard, 2013).

2.4.1. Bilinear interpolation (BLI) method

The schematic of the BLI method is shown in Figs. 1a and 1b where the symbols *a, b, c,* and *d* stand for the locations of known points. When a certain physical quantity, *P*, located at the unknown point *p* is predicted in terms of the quantities at *a, b, c,* and *d* using the BLI method, a three-step interpolation procedure is utilized and formulas are expressed below:

$$P_e = (1-\alpha)P_a + \alpha P_b \tag{1}$$

$$P_f = (1-\alpha)P_c + \alpha P_d \tag{2}$$

$$P_P = (1-\beta)P_e + \beta P_f \tag{3}$$

In these equations, α is the ratio of the distance between *a* and *e* to the distance between *a* and *b*; β is the ratio of the distance between *e* and *P* to the distance between *e* and *f*. The computational algorithm starts with finding the physical quality at *e* in terms of those at *a* and *b* through the linear interpolation, namely, Eq. (1). Meanwhile, the physical quality at *f* is calculated in terms of those at *c* and *d* via Eq. (2). After the physical quantities at *e* and *f* are obtained, the physical quality at *p* is estimated in terms those obtained at *e* and *f* by means of the same procedure, namely, Eq. (3).

2.4.2. Inverse distance weighted (IDW) method

In the IDW method, the formula for the physical quantity *P* at *p* predicted in terms of the quantities at *a, b, c,* and *d* is given below (Mito et al., 2011):

$$P(x') = \sum_{i=1}^{n} w_i P(x_i) \tag{4}$$

where n is the number of the surrounding known points and is 4 in this study; w_i are the weights assigned to the surrounding points and the subscript i stands for the neighbor points. The weights are calculated through the following function:

$$w_i = \frac{h_i^{-m}}{\sum_{i=1}^{n} h_i^{-m}} \tag{5}$$

where the exponent or power parameter m is a positive real number whose typical value is 2 (Mito et al., 2011), and h_i are the distances from the predicted location to the surrounding locations. Physically, the larger the value of m, the greater the influence of the location close to the predicted point (Mito et al., 2011).

2.5. Regression analysis

Regression analysis can be applied to establish the relationship between a certain quantity and some variables along with different orders. Lee &

Lee (2014) has analyzed the optimal operating conditions for the torrefaction of different types of biomass by regression analysis, and the correlations of weight loss and calorific value with respect to severity factor were conducted. To build up useful formulas for predicting the results of torrefaction, the correlations of three crucial indicators, consisting of biochar yield, enhancement factor of HHV, and energy yield, based on nondimensionalized torrefaction temperature and duration are established. The nondimensionalized temperature and duration are defined as follows:

$$t^{'} = \frac{t \quad (\text{min})}{60 \quad (\text{min})} \tag{6}$$

$$T^{'} = \frac{(\text{T}-200) \ \ (^{o}C)}{(300-200) \ \ (^{o}C)} \tag{7}$$

To evaluate the feasibility of the two interpolating methods and regression analysis in predicting the performance of torrefaction, the relative error between the predicted quantity and the measured result is calculated below

$$\text{Error}(\%) = \frac{\left| y_{predicted} - y_{measured} \right|}{y_{measured}} \times 100 \tag{8}$$

where $y_{predicted}$ is the predicted value from interpolation or regression method, and $y_{measured}$ denotes the measured result.

3. Results and discussion

3.1. Performance of torrefaction

The profiles of biochar yield, which is the weight ratio of torrefied biomass to its raw counterpart, under various combinations of torrefaction temperature and time are presented in Fig. 2a. When the biomass is torrefied at 200 °C, which belongs to light torrefaction (Chen & Kuo, 2010), the biochar yield is almost higher than 80% and linearly decreases with increasing time. On the other hand, the biochar yield at the torrefaction temperatures of 275 °C and 300 °C, which pertain to severe torrefaction, has a trend to exponentially decay. Overall, the biochar yield is in the range of 28.4-89.9 %, implying that the weight loss is between 10.1 % and 71.6 %. In the studies of Peng et al. (2012) and Chen et al. (2014), it has been illustrated that weight loss can be considered as an indicator to identify the torrefaction severity. The higher weight loss of biomass, the more severe the torrefaction degree.

The HHVs of produced biochars are listed in Table 1. With the combinations of adopted temperatures and durations, the HHV is between 16.3 MJ kg^{-1} (200 °C and 15 min) and 25.1 MJ kg^{-1} (300 °C and 60 min). It has been reported that the HHV of coal is normally between 25 MJ kg^{-1} and 35 MJ kg^{-1} (Chen et al., 2015c). Therefore, Table 1 suggests that the bagasse torrefied at 275 °C for 60 min or at 300 °C for 30 min or longer can produce upgraded fuel resembling coal inasmuch as the HHV is close to 25 MJ kg^{-1}. The profile of the enhancement factor of HHV, which is the HHV ratio of biochar to its untreated biomass, is displayed in Fig. 2b. As a whole, the enhancement factor ranges from 1.02 to 1.58, revealing that the torrefaction can effectively upgrade the biomass, especially at temperatures higher than 275 °C and duration longer than 45 min. For the light torrefaction (i.e., 200 °C and 225 °C), the enhancement factor tends to increase linearly with time. When the biomass undergoes torrefaction at 250 °C and 275 °C, the factor appears to exponentially grow with time, but its growing trend slows down at 300 °C. These results evidently reveal that the influence on duration on the quality of biochar depends intrinsically on temperature.

The profile of energy yield, which is the energy ratio of torrefied biomass to its parent biomass and equivalent to the multiplication of biochar yield and the enhancement factor (Chen et al., 2015a) is demonstrated in Fig. 2c. For the bagasse torrefied at 200 °C, the energy yield is always higher than 90%, irrespective of duration. In contrast, when the biomass is torrefied at 300 °C, the energy yield is lower than 60 %. In view of over 40% of energy lost at 300 °C, it is thus pointed out that this temperature may be too high for pretreating the bagasse, even though the quality (or calorific value) of the biomass is improved significantly.

3.2. Atomic H/C and O/C ratios

The atomic H/C and O/C ratios are highly related to the calorific value of a fuel (Chen et al., 2015c). The weight percentages of C, H, N, and O (dry-ash-free basis) in the torrefied materials are given in Table 2. Based on the analysis, the van Krevelen diagram is displayed in Fig. 3 in which the atomic H/C and O/C ratios of raw and upgraded materials are plotted. While the thermal degradation of biomass proceeds in torrefaction, the decarbonization, dehydrogenation, and deoxygenation mechanisms occur (Chen et al., 2012a). The dehydrogenation and deoxygenation reactions are more drastic compared to the decarbonization reaction (Chen et al., 2016), and, therefore, both the atomic H/C and O/C ratios decrease when the torrefaction temperature or duration is raised. Within the investigated ranges of torrefaction temperature and duration, the atomic H/C and O/C ratios are in the ranges of 0.79-1.71 and 0.29-0.85, respectively. It has been known that the H/C and O/C ratios of coal are smaller than 1.0 and 0.3, respectively (van der Stelt et al., 2011). Fig. 3 suggests that the H/C and O/C ratios of the bagasse torrefied at 300 °C are close to those of coal. These characteristics are consistent with the results of measured HHV shown in Table 1. The results of Daniyanto et al. (2015) and Valix et al. (2017) are also shown in Fig. 3. The data of Daniyanto et al. are close to the results of the present work, whereas the results of Valix et al. are lower, presumably due to different sugarcane bagasse species adopted.

The regression line of the H/C and O/C ratios are also plotted in Fig. 3. The coefficient of determination (i.e., R^2) is 0.9858, elucidating the strong linear correlation between the two ratios. This implies, in turn, that there exists a linear relationship of dehydrogenation and deoxygenation from the thermal degradation of the biomass. The slope of the regression line is 1.57 which is close to those of bamboo (=1.69) (Li et al., 2015) and pine sawdust (=1.71) (Gong et al., 2016), reflecting that the impact of torrefaction on the atomic H/C ratio is larger than on the atomic O/C one by factors of approximately 1.57-1.71. The examination of the van Krevelen diagrams of microalgae residues *Chlamydomonas sp*. JSC4 (Chen et al., 2015b) and *Chlorella vulgaris* ESP-31 (Chen et al., 2015a) indicated that the slopes of their regression lines were 2.58 and 2.67, respectively. This reveals that the influence of the thermal pretreatment on the difference between the atomic H/C and O/C ratios is intensified when microalgae residues are torrefied. This can be explained by the main components of carbohydrates and proteins in microalgae residues which are more sensitive to torrefaction.

3.3. Bilinear interpolation (BLI) method

It has been illustrated that interpolation can be used to predict the combination of temperature and duration for evaluating the optimal torrefaction operation (Chen et al., 2015d). To evaluate the feasibility of the BLI method in predicting the performance of torrefaction, five different combinations of temperature and holding time, which cover light, mild, and severe torrefaction along with shorter, intermediate, or longer durations, are selected and shown in Table 3 (i.e., Cases 1-5). The obtained values of the three physical quantities are also given in the table and plotted in Fig. 2. Meanwhile, the predicted values of the three quantities by means of the BLI, IDW, and regression analysis are tabulated in Table 4. Based on the values in Table 3, the errors between the predicted quantities and measured ones are displayed in Table 5. The table depicts that the errors of the three physical quantities in most cases are smaller than 5 %, implying that the BLI method is able to accurately estimate the performance of the bagasse torrefaction. The errors of biochar and energy yields in Case 4 are 6.63 % and 6.32 %, respectively. The two higher errors may be attributed to the higher sensitivity of thermal decomposition of hemicellulose (Chen & Kuo, 2010), which accounts for 30.82 % in the bagasse, in Case 4.

3.4. Inverse distance weighted (IDW) method

A variety of values of power parameter *m* such as *m*=1-10 (Bekele et al., 2003; Jing & Wu, 2013; Ping et al., 2004; Tomczak, 1998) have been adopted for interpolation. For example, Ping and Green (Ping et al., 2004) used *m*=1-5 in the IDW route to determine the spatial weights matrix for modeling autocorrelation functions when exploring spatial dependencies in cotton yield. In the present study, in addition to evaluating the potential of the IDW method for predicting the performance of torrefaction, the influence of the value of the power parameter on the predictions is also taken into account where *m*=1, 4, and 7 are considered. Fig. 4 shows the profiles of error in predicting the biochar yield, enhancement factor, and energy yield under the operations of the five cases (Table 3), and depicts that the errors are lower than 10 % (most of the cases are smaller than 5 %). Similar to the BLI method shown in Table 5, the prediction of the enhancement factor (Fig. 4b) has the lowest error when compared to those of the biochar and energy yields (Figs. 4a and 4c). In particular, the error is always lower than 5 % when *m*=1 is adopted. Moreover, the calculation with m=1 is much easier than higher power parameters. Accordingly, the IDW method along with *m*=1 is recommended for the prediction of torrefaction performance. This result further implies that the prediction of torrefaction is relatively insensitive to the nearest sampled point in the IDW method (Mito et al., 2011).

3.5. Regression analysis

Unlike the BLI and IDW methods where the predicted quantities are obtained in terms of those of surrounding four points, correlations conducted from regression analysis are obtained from all the operating conditions (i.e., 20 points shown in Fig. 2). Table 6 lists the first order and second order regression formulas of the biochar yield, enhancement factor, and energy yield. With a confidence interval of 95%, the coefficient of determination of the regression analysis is larger than 0.90 and the standard deviation is less than 0.063, rendering the good correlation from the analysis. Table 6 further reveals that the second order analysis can provide better correlations, especially in the enhancement factor where the coefficient of determination rises from 0.904 to 0.958 when the order increases from 1 to 2. In examining the equations from the first order regression analysis, it can be found that the coefficients of nondimensional temperature are always higher than that of nondimensional time, regardless of which quantity is analyzed (Table 6). It follows that the temperature has a greater influence on the physical qualities than the time, and this conclusion has also been addressed in other studies (Bach et al., 2013; Chen et al., 2015a). As for the second order analysis, the influences of temperature and duration on the quantities cannot be identified directly, stemming from the coupling of the two factors in the equations.

The error profiles of the three physical quantities between the regression analysis and measurements of the five cases in Table 3 are shown in Fig. 5. For the first order analysis, Fig. 5a depicts that the error is always lower than 10 %, suggesting that the three physical quantities can be appropriately predicted. When the second order analysis is performed, the maximum error is 6.03 % which occurs at the energy yield of Case 4. A comparison of error profiles shown in Table 5 and Figs. 4 and 5 indicates that the IDW method along with power parameter of 1 (i.e., m=1) provides the lowest error and thus the most precise prediction in the biochar yield, enhancement factor, and energy yield (Fig. 4). Alternatively, the predictions based on the BLI method have the largest error (Table 5), but the maximum error is 6.63 % which is merely slightly higher than that (=4.99 %) based on the IDW method with m=1. With regard to regression analysis, the second order analysis can also control the error below around 6%. The established correlations from the regression analysis possess the advantage of predicting the three physical quantities directly, and is thus recommended, even though six terms are required in the correlations.

The energy yield is obtained from the solid yield multiplied by the enhancement factor (Chen et al., 2015c), implying that the three physical quantities are mathematically dependent. Therefore, instead of the direction prediction from the experimental data of energy yield, values of other the prediction of the energy yield can also obtained from the predicted solid yield and enhancement. The analysis suggests that the values of the energy yields from the two different predction methods

4. Conclusions

The results show that torrefaction with higher severity such as at 275 °C for 60 min or at 300 °C for 30 min or longer can upgrade the bagasse into biochar which possesses calorific value in a comparable level to coal. However, the torrefaction temperature of 300 °C leads to lower energy yield and is thus not recommended. The three physical quantities predicted by the BLI, IDW interpolation, and regression analysis are compared with each other. Overall, the three methods with appropriate power parameters (e.g., m=1) or orders (e.g., order=2) can accurately predict the biochar formation and torrefaction performance.

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Figure captions

Figure 1. Schematics of (a) unknown point, (b) known points and bilinear interpolation, and (c) inverse distance weighting interpolation.

Figure 2. Profiles of (a) biochar yield, (b) enhancement factor of HHV, and (c) energy yield at various operating conditions of torrefaction.

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Figure 5. Error profiles of biochar yield, enhancement factor, and energy yield from (a) first order and (b) second order regression analyses.

Table 1. HHV of torrefied sugarcane bagasse at selected operating conditions of torrefaction.

Duration (min)	**Temperature (°C)**				
	200	**225**	**250**	**275**	**300**
15	16.28	16.38	18.14	18.85	22.66
30	16.55	17.15	18.69	19.48	24.40
45	16.85	17.56	19.09	21.78	24.68
60	17.16	17.93	21.22	24.25	25.07

Table 2. Element analysis (wt%, dry-ash-free) of torrefied sugarcane bagasse at selected operating conditions of torrefaction.

Duration	**Temperature (°C)**				
(min)	**200**	**225**	**250**	**275**	**300**
	Carbon (C)				
15	43.76	44.23	48.16	55.31	58.31
30	44.18	46.72	50.00	62.84	64.21
45	46.10	46.98	51.70	63.76	67.11
60	46.80	47.23	52.60	67.51	68.03
	Hydrogen (H)				
15	6.23	6.11	5.35	5.30	5.13
30	6.02	5.91	5.38	4.88	4.82
45	5.92	5.88	5.39	4.52	4.66
60	5.88	5.79	5.44	4.49	4.52
	Nitrogen (N)				
15	0.57	0.58	0.52	0.54	0.32
30	0.59	0.62	0.61	0.31	0.58
45	0.61	0.42	0.31	0.55	0.33
60	0.65	0.70	0.33	0.88	0.31

	Oxygen (O)				
15	49.44	49.08	45.97	38.85	36.24
30	49.21	46.75	44.01	31.97	30.39
45	47.37	46.72	42.60	21.17	27.90
60	46.67	46.28	41.63	27.12	27.14

Table 3. Biochar yield, HHV, and energy yield of torrefied sugarcane bagasse at five different operating for interpolating prediction

Case	Operating conditions (°C/min)	Biochar yield (%)	HHV (MJ kg^{-1})	Energy yield (%)
1	212/20	85.60	16.89	90.68
2	220/50	74.44	17.86	83.38
3	240/35	73.04	18.00	82.47
4	260/40	59.36	19.51	72.65
5	285/55	32.67	24.89	51.00

Table 4. Predicted biochar yield, enhancement factor, and energy yield by various methods.

Case	Operating conditions (°C/min)	Biochar yield (%)	Enhancement Factor	Energy yield (%)
BLI				
1	212/20	87.52	1.03	90.43
2	220/50	77.32	1.10	84.94
3	240/35	69.82	1.14	79.37
4	260/40	55.43	1.24	68.05
5	285/55	33.71	1.51	50.49
IDW (*m*=1)				
1	212/20	86.84	1.04	89.95
2	220/50	77.96	1.10	85.44
3	240/35	69.74	1.14	79.35
4	260/40	56.72	1.23	69.02
5	285/55	33.91	1.50	50.44
IDW (*m*=4)				
1	212/20	87.66	1.03	90.42
2	220/50	76.31	1.10	84.20
3	240/35	67.39	1.16	77.82
4	260/40	61.29	1.20	73.15
5	285/55	34.98	1.50	52.07
IDW (*m*=7)				
1	212/20	88.32	1.03	90.80
2	220/50	76.55	1.10	84.36
3	240/35	66.06	1.17	77.01
4	260/40	63.39	1.19	75.00

5	285/55	35.36	1.50	52.96
1st order regression analysis				
1	212/20	89.73	0.99	93.68
2	220/50	74.01	1.14	82.08
3	240/35	68.45	1.18	77.61
4	260/40	55.39	1.29	67.68
5	285/55	35.78	1.47	52.89
2nd order regression analysis				
1	212/20	87.81	1.02	91.00
2	220/50	74.97	1.11	83.43
3	240/35	68.89	1.13	78.19
4	260/40	55.83	1.25	68.26
5	285/55	34.32	1.49	50.83

Table 5. Errors table of biochar yield, enhancement factor, and energy yield from bilinear interpolation method.

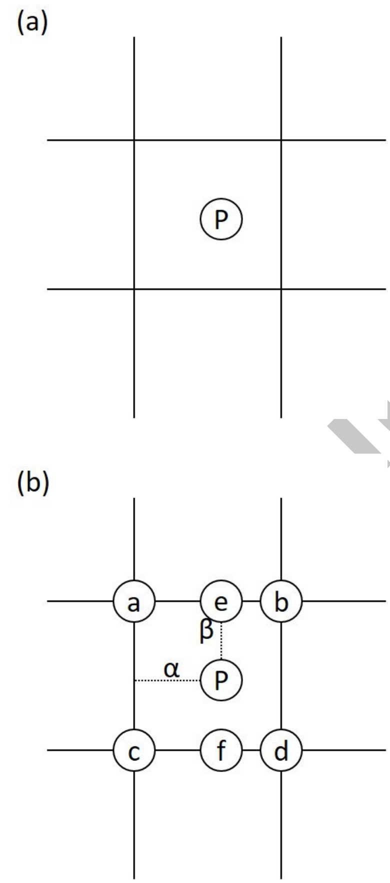
Case	**Operating conditions (°C/min)**	**Biochar yield (%)**	**Enhancement Factor (%)**	**Energy yield (%)**
1	212/20	2.24	2.37	0.28
2	220/50	3.86	1.81	1.88
3	240/35	4.41	1.13	3.76
4	260/40	6.63	1.36	6.32
5	285/55	3.19	3.44	1.00

Table 6. Regression analyses and correlations of biochar yield (BY), enhancement factor (EF) of HHV, and energy yield (EY).

Quantity	Regression equation	R^2	σ *
1st order			
BY	$1.0394323 - 0.559324T' - 0.224944t'$	0.960829	0.045444
EF	$0.8624428 + 0.4725557T' + 0.2195347t'$	0.904203	0.062837
EY	$1.042628 - 0.42811T' - 0.16341t'$	0.936278	0.044737
2nd order			
BY	$1.020226 - 0.314099T' - 0.339488t' - 0.147003T'^2 + 0.1544976t'^2 - 0.157157T' \times t'$	0.973566	0.041138
EF	$1.003315 - 0.01959T' + 0.000783t' + 0.351189T'^2 + 0.084791t'^2 + 0.225525T' \times t'$	0.957685	0.046021

EY	$1.013781 - 0.09464T' - 0.31128t' - 0.19558T'^2 + 0.206553t'^2 - 0.22063T' \times t'$	0.975998	0.030255

* Standard deviation


(a)
P
(b)
a
e
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β
α
P
c
f
d

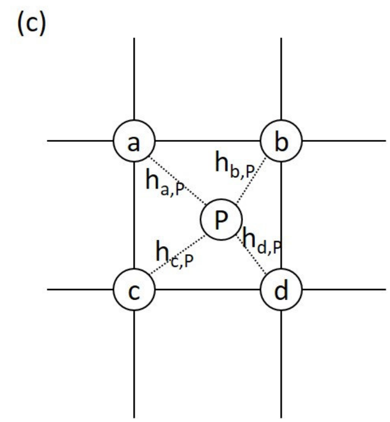


Figure 1. Schematics of (a) unknown point, (b) known points and bilinear interpolation, and (c) inverse distance weighting interpolation.

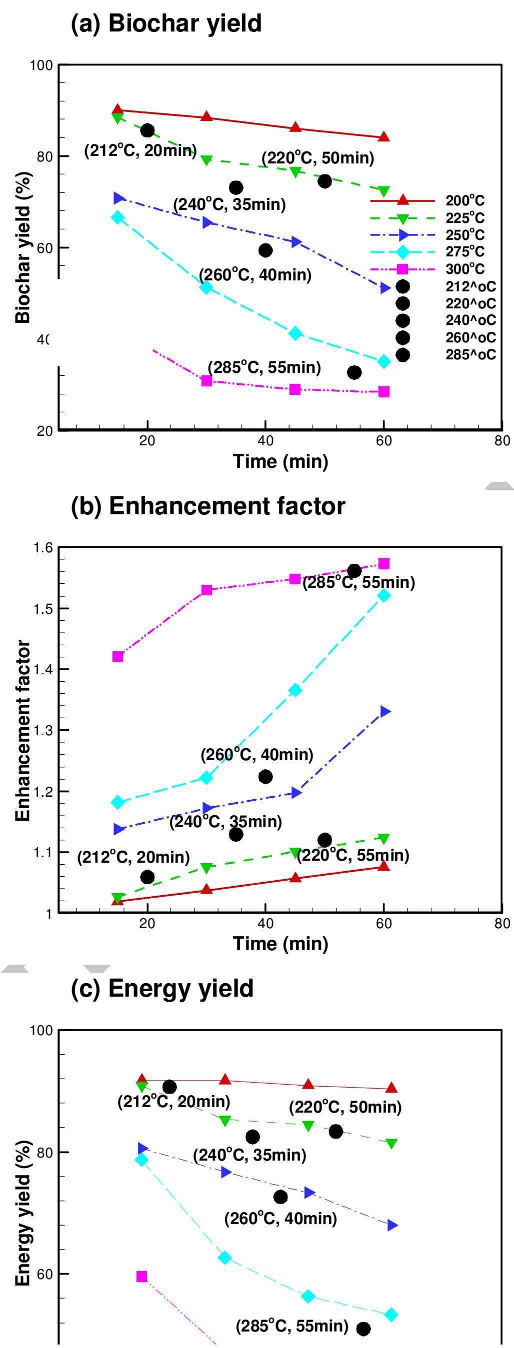

(a) Biochar yield
Biochar yield (%)
Time (min)
(212°C, 20min)
(220°C, 50min)
(240°C, 35min)
(260°C, 40min)
(285°C, 55min)
200°C
225°C
250°C
275°C
300°C
212^oC
220^oC
240^oC
260^oC
285^oC
(b) Enhancement factor
Enhancement factor
Time (min)
(285°C, 55min)
(260°C, 40min)
(240°C, 35min)
(212°C, 20min)
(220°C, 55min)
(c) Energy yield
Energy yield (%)
(212°C, 20min)
(220°C, 50min)
(240°C, 35min)
(260°C, 40min)
(285°C, 55min)

Figure 2. Profiles of (a) biochar yield, (b) enhancement factor of HHV, and (c) energy yield at various operating conditions of torrefaction.

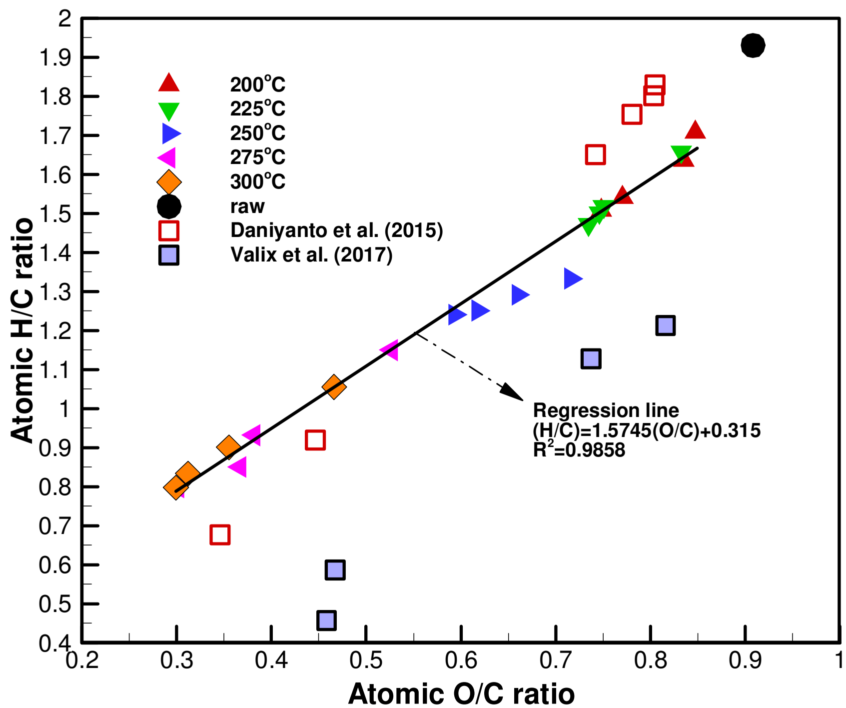


Figure 3. Profiles and linear regression of atomic H/C ratio versus atomic O/C ratio (van Krevelen diagram).

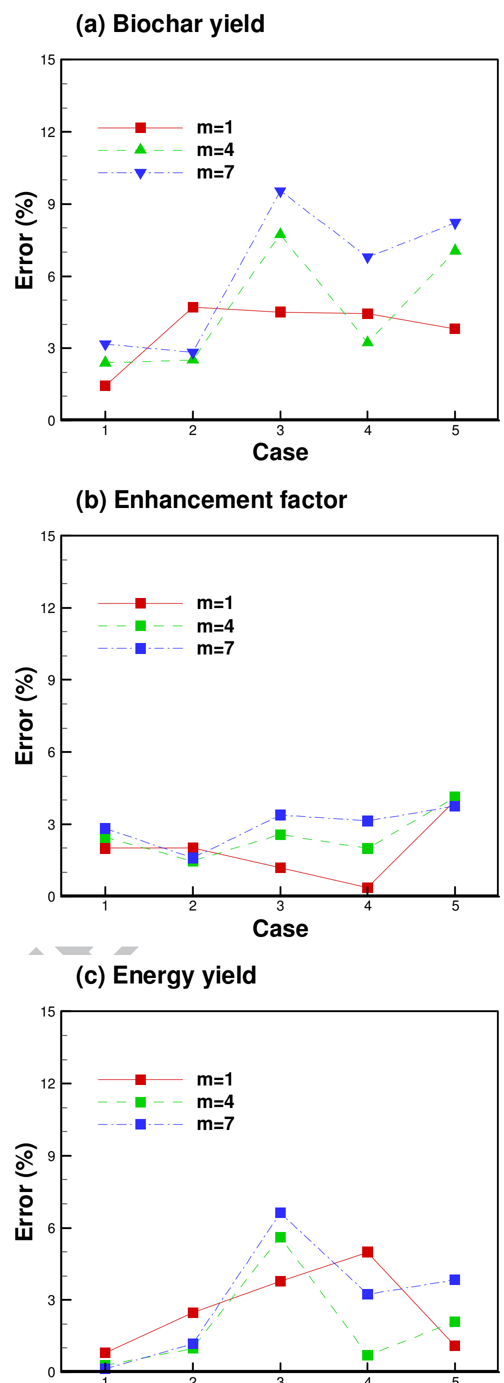
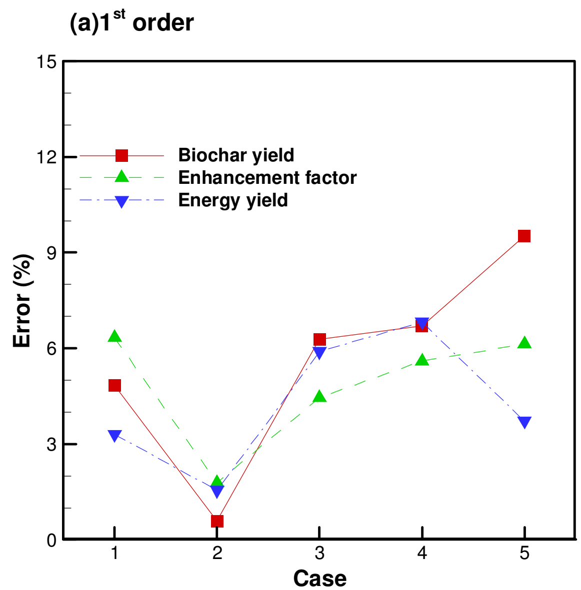

(a) Biochar yield
Error (%)
Case
m=1
m=4
m=7
(b) Enhancement factor
Error (%)
Case
m=1
m=4
m=7
(c) Energy yield
Error (%)
m=1
m=4
m=7

Figure 4. Error profiles of (a) biochar yield, (b) enhancement factor, and (c) energy yield from inverse distance weighting interpolation at three values of power parameter (*m*=1, 4, and 7).


(a)1st order
Biochar yield
Enhancement factor
Energy yield
Error (%)
Case
0
3
6
9
12
15
1
2
3
4
5

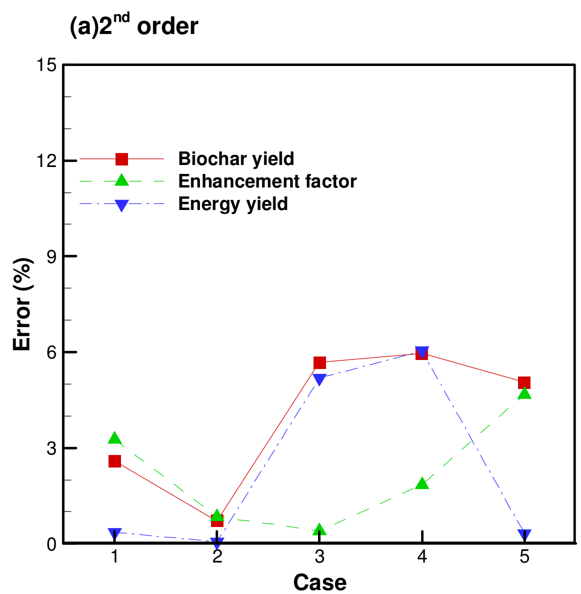

(a)2nd order
Biochar yield
Enhancement factor
Energy yield
Error (%)
Case
0
3
6
9
12
15
1
2
3
4
5

Figure 5. Error profiles of biochar yield, enhancement factor, and energy yield from (a) first order and (b) second order regression analyses.

Highlights

1. Sugarcane bagasse is torrefaction at various combinations of temperature and durations.
2. BLI, IDW, and regression analysis are used to predict torrefaction performance.
3. The three methods are all feasible for predicting the performance.
4. The power parameter of unity in IDW provides the best predictions.
5. The second order regression analysis gives a more reasonable approach.

Graphical Abstract