



Enhancing torrefaction process efficiency for biochar production from filter cake residue in the sugar industry

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ABSTRACT

The torrefaction process is a promising technique for enhancing the quality of solid biomass fuels. This study investigates the effects of torrefaction on biochar produced from filter cake residue, a byproduct of the sugar industry. The primary objectives were to evaluate the impact of process parameters on biochar properties and identify optimal conditions for maximizing the higher heating value (HHV). Filter cake residue was subjected to torrefaction at temperatures ranging from 220–340°C under an inert atmosphere. The influence of particle size (20, 60, and 100 mesh), nitrogen flow rate (20–30 ml/min), temperature (220–340°C), and residence time (30–90 min) on biochar properties was examined using response surface methodology. Proximate analysis revealed that torrefaction significantly reduced moisture, volatile matter, and ash content while increasing fixed carbon content. The maximum HHV of 21.9571 MJ/kg was achieved at a particle size of 20 mesh, nitrogen flow rate of 25 ml/min, temperature of 340°C, and residence time of 60 min. The experimental results agreed with predicted values from the developed models, with an average error of 3.64%. Optimal torrefaction conditions were determined to be a particle size of 21.77 mesh, nitrogen flow rate of 22.50 ml/min, temperature of 311.13°C, and residence time of 42.58 min, yielding a maximum HHV of 18.4853 MJ/kg. These findings demonstrate the potential of torrefaction for upgrading filter cake residue into a high-quality solid biofuel, providing a sustainable solution for waste utilization in the sugar industry.

Keywords: Biomass, Torrefaction process, Filter cake residue

INTRODUCTION

Biomass is considered a highly significant energy source because it is a natural energy reservoir that can be utilized for energy production without contributing to the greenhouse effect. This is attributed to the fact that carbon dioxide generated during combustion is utilized for photosynthesis in plant growth, leading to cyclic carbon circulation without substantial atmospheric release. Moreover, biomass fuel is cost-effective as it can be produced domestically sustainably, reducing the need to import and generate local income [1]. Recognizing these advantages, the government acknowledges the importance and benefits of biomass energy. Thailand has formulated policies to promote energy security to boost research and development in alternative energy derived from biomass, aligning with Thailand's Thirteenth economic and societal development plan (2023–2027) [2].

Biochar, a carbon-rich material produced from biomass or organic substances from natural decay or agricultural waste, is generated through a controlled pyrolysis process at low oxygen levels. This process is called pyrolysis under anaerobic or limited oxygen

conditions. In this way, biochar with various properties suitable for use as fuel is obtained. An ideal biochar possesses a high heating value (HHV) and meets other standard criteria. However, the production of biochar from biomass is not yet fully efficient. Factors such as temperature and time during torrefaction result in heat loss and insufficient product yield. Consequently, extensive expenses are incurred [3]. Hence, this research addresses this issue by determining the most suitable conditions for producing biochar from filter cake residue, a type of biomass.

This study investigates the effects of the torrefaction process on biofuel produced from filter cake residue and identifies the most suitable conditions. The study examines the influence of variables affecting the torrefaction process, including biomass particle size, nitrogen gas flow rate, temperature, and torrefaction time [4–7].

MATERIALS AND METHODS

Material preparation

The biomass material used in this research is filter cake residue obtained from a sugar factory.

Figure 1(a) shows the raw material of filter cake residue used in the research. The material was dried under sunlight for 2 days, as shown in Figure 1(b). It was ground to fine particles and sieved through three sizes of (a) 20, (b) 60, and (c) 100 mesh, as shown in Figure 2. All three-size powders were put into ziplock bags for further analysis under the torrefaction process. However, the proximate composition of the sample, that is, volatile matter, moisture, fixed carbon, and ash, was determined. The samples used were raw filter cake residue and filter cake residue after the torrefaction process.

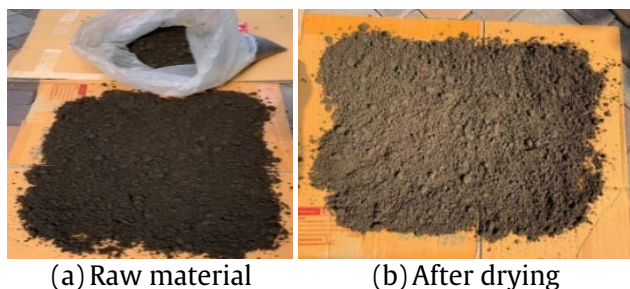


Figure 1 Filter cake residue: (a) raw material and (b) after drying.



Figure 2 Filter cake residue with different particle sizes of (a) 20, (b) 60, and (c) 100 mesh.

Experimental design using design expert program

In the torrefaction process, the independent variables for the experiments include biomass particle size (mesh), nitrogen gas flow rate (ml/min), temperature (°C), and time (min). The dependent variable is biomass's higher heating value (HHV) in MJ/kg.

In this work, the Box-Behnken design (BBD) method using the Design Expert V.13.0 program was employed for statistical analysis and prediction of the experimental outcomes. The study focused on the influence of 3 levels (minimum, mean, maximum) of 4 variables (X_1 , X_2 , X_3 , X_4) as presented in Table 1, under the conditions specified in Table 2.

Table 1 Experimental design by BBD method.

Parameter	Symbol	Unit	Min.	Mean	Max.
Particle size	X_1	mesh	20	60	100
N ₂ flow rate	X_2	ml/min	20	25	30
Temperature	X_3	°C	220	280	340
Time	X_4	min	30	60	90
High heating value	Y_1	MJ/kg	-	-	-

Table 2 Conditions of torrefaction process.

Run No.	Particle size (mesh)	Flow N ₂ (ml/min)	Temperature (°C)	Time (min)	HHV (MJ/kg)
1	60	20	340	60	18.3352
2	60	20	280	30	16.6152
3	20	25	280	30	19.6237
4	60	20	280	90	16.4797
5	100	25	280	90	16.7569
6	60	30	340	60	20.2209
7	100	25	280	30	16.8694
8	20	25	220	60	18.7078
9	60	30	280	90	18.1508
10	100	25	220	60	16.5795
11	100	25	340	60	18.5945
12	60	25	220	30	16.7533
13	20	30	280	60	20.5835
14	60	25	340	90	19.4425
15	60	25	220	90	16.6551
16	60	25	280	60	16.5356
17	60	25	280	60	17.5356
18	60	30	280	30	18.2773
19	100	30	280	60	17.2832
20	100	20	280	60	16.1719
21	20	25	280	90	19.4872
22	60	25	280	60	17.8356

Run No.	Particle size (mesh)	Flow N ₂ (ml/min)	Temperature (°C)	Time (min)	HHV (MJ/kg)
23	60	25	280	60	17.3412
24	60	25	280	60	17.2914
25	60	20	220	60	15.9001
26	20	20	280	60	17.8521
27	20	25	340	60	21.9571
28	60	30	220	60	17.3487
29	60	25	340	30	19.3419

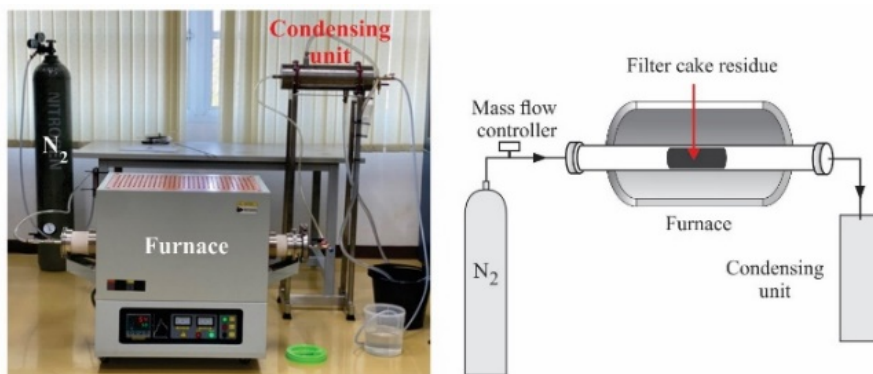


Figure 3 Shows (a) a photograph and (b) a schematic diagram of the experimental setup of the torrefaction process.

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It is seen from Table 2 that the maximum HHV of 21.9571 MJ/kg was obtained from run no. 27, where particle size, N₂ flow rate, temperature, and time were 20 mesh, 25 ml/min, 280°C and 30 min, respectively. The HHVs obtained from the design model were then compared with those of the experimental torrefaction process, as described in the next Section.

Torrefaction process

Figure 3 shows the schematic diagram of the torrefaction experiment. The reactor for loading filter cake residue was made of cylindrical stainless steel with a length of 160 mm and a diameter of 54.6 mm. It was placed inside a horizontal tube furnace with a length of 120 cm (Vacuum 1,400 degree Tube Furnace, Model PN:SK2-7-14PD3). The sample temperature was measured using 4 thermocouples introduced through the top flange of the reactor. A temperature controller of the furnace controlled the temperature.

About 20 g of filter cake residue sample was uniformly distributed inside the sample basket and placed in the uniform heated zone of the reactor prior to the experiment. The reactor lid was closed, and a mass flow controller controlled nitrogen gas flow into the reactor. The nitrogen flow rate was maintained for 30 min to remove the air from the reactor chamber and ensure inert condition. The sample was heated

from the room to the desired temperature with a rate of 10°C min⁻¹ under a nitrogen atmosphere. The gas leaving the torrefaction reactor was cooled by a condensing unit using two lines of the condenser ice bath, where most of the tar and water were collected. To compare the HHVs obtained from the design model, as shown in Table 2, with those obtained from the experimental torrefaction process, we conducted the experiments at 4 conditions, including run no. 27 (maximum HHV of 21.9571 MJ/kg), run no. 25 (minimum HHV of 15.9001 MJ/kg), run no. 13 and run no. 19.

Measurement of Higher Heating Value (HHV)

The heating value indicates the amount of energy released during fuel combustion (biomass) per unit weight in the form of heat. The heating value of each fuel type varies depending on the characteristics and components of the biomass. Higher heating value (HHV) refers to the heat energy released from the complete combustion of fuel (Gross calorific value), including the latent heat of vaporization of water.

Generally, the higher heating value from biomass is analyzed using a Bomb calorimeter, which measures the heat energy from burning samples in the calorimeter. It operates on the principle that the energy accumulated in the chemical bonds of the substance is released when the substance is burned, known as the heat of combustion. In the Bomb calorimeter, biomass combustion causes a temperature change. Then, the higher heating value is determined as the heat released during combustion from initial to final temperatures as described by the equation:

$$HHV = \frac{W\Delta T}{m}$$

where ΔT is the increased temperature ($^{\circ}\text{C}$), W is the energy equivalent (EE) of Bomb calorimeter ($\text{cal}/^{\circ}\text{C}$) and m is the weight of the sample (g). In this work, the Bomb calorimeter manufactured by IKA was designed for scientists. The Model Calorimeter C1 was used to measure the high heating value of the combustion of biomass filter cake. It consisted of the calorimeter, combustion chamber, and chiller.

RESULTS AND DISCUSSION

Table 3 shows the proximate analysis of raw filter cake residue and torrefied filter cake residue after the torrefaction process of run no. 27 (particle size, N_2 flow rate, temperature, and time were 20 mesh, 25 ml/min, 280°C and 30 min, respectively). Raw filter cake residue has a very high amount of volatile matter and high moisture content, resulting in its low heating value. In addition, the raw filter cake has low carbon that carbon, which also results in its low heating value. For

torrefied filter cake residue, the volatile matter decreased from 72.76 to 51.70%, and the ash decreased from 2.15 to 1.81%, while the fixed carbon increased from 15.40 to 38.74%, increasing the heating value.

Table 3 Proximate analysis (wt%, d.b.).

Proximate composition	Before torrefaction	After torrefaction
Volatile matter	72.76	51.70
Moisture	9.69	7.75
Fixed carbon	15.40	38.74
Ash	2.15	1.81

The experimental torrefaction process was conducted for 4 biomass samples of run nos. 27, 13, 19, and 25 as described in Section Measurement of Higher Heating Value (HHV). The results of those samples on HHVs are given in Table 4. The average difference value of HHV between the simulation model and experiment was 3.64%.

Table 4 Torrefaction process experiment at 4 conditions.

Run No.	Particle size (mesh)	N_2 flow rate (ml/min)	Temperature ($^{\circ}\text{C}$)	Time (min)	HHV (MJ/kg) Simulation	HHV (MJ/kg) Experiment	Error
27	20	25	340	60	21.9571	20.7453	5.52
13	20	30	280	60	20.5835	19.9954	2.86
19	100	30	280	60	17.2832	16.9853	1.72
25	60	20	220	60	15.9001	15.1872	4.48

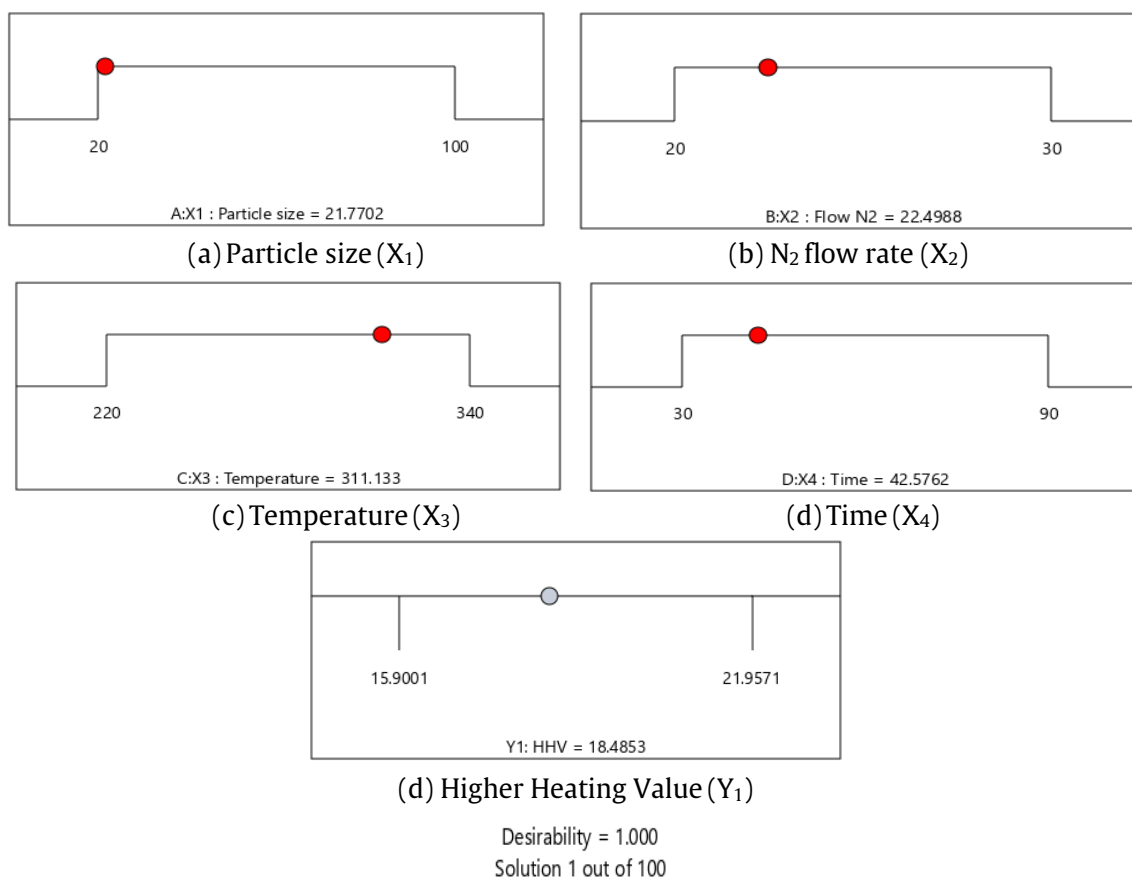


Figure 4 Optimal conditions for the torrefaction process of filter cake residue.

To find the optimum point for the torrefaction process of filter cake residue in this work, by using the Design Expert v13.0 program, the most suitable conditions for the process were obtained, as shown in Figure 4. That is: a) particle size (X_1) was 21.7702 mesh, b) N_2 flow rate (X_2) was 22.4988 mL/min, c) temperature (X_3) was 311.1330°C, and d) time (X_4) was 42.5762 min and gave the maximum HHV of 18.4853 MJ/kg.

CONCLUSIONS

This study investigated the torrefaction process to enhance the fuel properties of filter cake residue, a waste biomass material from the sugar industry. The raw filter cake was sun-dried, ground, and sieved to obtain three particle sizes: 20, 60, and 100 mesh. Design Expert v.13.0 software was employed to design the experiments and analyze the results. The influence of four independent variables, namely particle size (X_1), N_2 flow rate (X_2), temperature (X_3), and residence time (X_4), on the higher heating value (HHV) of the torrefied biomass was examined. Proximate analysis revealed that torrefaction significantly altered the composition of the filter cake residue. Volatile matter, moisture, and ash contents decreased while fixed carbon content increased, resulting in an overall improvement in the heating value of the biomass. The experimental HHV values agreed with the predicted values, with an average deviation of 3.64%.

Response surface methodology was employed to identify the optimal torrefaction conditions for maximizing the HHV of the torrefied filter cake. The optimal parameters were determined to be a particle size of 21.77 mesh, N_2 flow rate of 22.50 mL/min, temperature of 311.13°C, and residence time of 42.58 min. Under these conditions, a maximum HHV of 18.4853 MJ/kg was predicted. The findings of this study demonstrate the potential of torrefaction as an effective technique for upgrading the fuel properties of filter cake residue. A high-quality solid biofuel can be produced from this abundant waste biomass by optimizing the process parameters. Using filter cake residue for biofuel production provides a sustainable solution for waste management in the sugar industry and contributes to developing renewable energy sources.

Further research is recommended to investigate the feasibility of scaling up the torrefaction process and to assess the techno-economic and environmental aspects of utilizing torrefied filter cake as a biofuel. Additionally, the properties and performance of the torrefied biomass in various combustion systems should be evaluated to ensure its suitability as a fuel substitute.

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