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Research article

Simulation and experimental study of biocoal production via dry torrefaction of palm empty fruit bunch

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Abstract

Importance of the work: The optimum conditions of biocoal and techno-economic analysis are important in determining the potential of biocoal production based on a torrefaction.
Objectives: 1) To experiment with torrefaction for simulation; 2) to simulate and design biocoal production; and 3) to perform techno-economic analysis.
Materials & Methods: A palm empty fruit bunch (PEFB) sample from Thailand was used in the torrefaction experiment. The simulation used the Aspen Plus to model the torrefaction. Investment and optimization aimed to maximize profitability. The torrefaction temperature was set at 200–300°C, with a heating rate of 10°C/min and a residue time of 10-50 min.
Results: The yield of biocoal from PEFB at 300°C and a residue time of 30 min was 56.13%, which was higher than the biogas and bio-oil yields. There was a good correlation between the PEFB yield and the temperature factor at 300–320°C, suggesting that this temperature range influenced the yield of PEFB, making it a suitable biomass material for making biocoal. The simulation generated 1,876.25 t/d of PEFB at 300°C, producing 21,631.70 kg/hr of char, 14,530.29 kg/hr of gas, 1,279.31 kg/hr of bio-oil and 40,736.10 kg/hr of vapor. The optimal utility cost was USD 4.06 million, with a 20 yr life cycle and a total capital investment of USD 20.38 million.
Main finding: In the simulation using PEFB, the production of biocoal decreased with increasing temperature due to faster devolatilization and a reduction in carbon levels. The conceptual design of biocoal production was presented with supported data from experiments and techno-economic analysis.

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Introduction

Lignocellulosic biomass can be processed using thermochemical processes and can selectively convert biomass into solid, liquid or gaseous fuels in a short time (Ninduangdee and Kuprianov, 2013). Torrefaction is known as mild pyrolysis because the conversion process usually occurs at a low temperature in the range 200–300°C (Wilk and Magdziarz, 2017; Hernowo et al., 2022). Biomass degradation during torrefaction can be divided into several steps based on the temperature that are related to the changes that occur to the biomass components. In the initial stage, water is removed from the biomass at around 40°C. After the release of the moisture contained in the material, the decomposition of hemicellulose becomes the primary reaction that lasts up to 270°C (Lee et al., 2021). At this temperature, small amounts of lignin and cellulose also decompose. At 300°C, the degree of lignin and cellulose decomposition increases, which is not recommended to obtain high-mass yield solids. On the other hand, reducing the amounts of biomass components, which tend to be small due to torrefaction, is sufficient to obtain a large amount of high-mass solids (Chen et al., 2016). The current study applied this process to determine the optimum biocoal production derived from a palm empty fruit bunch (PEFB). The comparison and investigation phases used laboratory data to measure the final produced yield based on the experimental-scale thermodynamic reaction (Bhattacharya, 2021). Furthermore, any degradation of hemicellulose, which has a low energy content, results in retaining a large portion of the original mass of the raw material without much loss of its initial energy.

The design and optimization of biocoal production plants require accurate and reliable models to assess their performance and economic viability (Liu et al., 2022). Many studies have used experimental methods to investigate the feasibility of various options. These methods can be time-consuming, expensive, and limited in their ability to provide detailed information about the underlying processes (Tavan and Hosseini, 2013). The Aspen Plus software can be used to simulate the entire process in a virtual environment to identify and address potential issues before the actual plant is constructed, saving the time and cost associated with plant modifications and improvements and leading to increased profitability and competitiveness in the market (Jasper et al., 2023).

In the current study, the purpose of using Aspen Plus in combination with laboratory data was to determine the corrections to the optimal torrefaction-to-feed ratio, temperature, and pressure for the biocoal process applied to describe the correlation between the process variables and the output response. This information can optimize biocoal production by reducing CO_2 emissions and utility costs. Optimization of the PEFB biocoal plant had three objectives: 1) to design and test the simulation model of the dry torrefaction process regarding its technological and economic feasibility; 2) to assess the technology and economic feasibility of dry torrefaction based on the experimental results; and 3) to compare the simulation and experimental results regarding the technological and economic feasibility of dry torrefaction.

Materials and Methodology

Experimental

Biomass collection and preparation

This study involved experimental research on a specific type of biomass torrefaction process using PEFB obtained from a palm plantation in Thailand. The PEFB was prepared for experimentation by cutting and drying in direct sunlight for 2 d, followed by grinding and screening to produce solid particles with a size range of 2–250 mm. It was assumed that all components of this raw material had the same water content and that the values obtained represented PEFB commonly found in the process. Regardless, the initial water content (in dry PEFB) would not have any significant effect on the torrefaction that occurs at high temperatures. Following grinding and screening, the material was stored in a dry, sealed container before conducting the experiment. During each experiment, a predetermined amount of raw material was fed into the laboratory reactor and torrefied under an N_2 atmosphere. N_2 was used to control both temperature and the absence of oxygen in the torrefaction, with the temperature inside the reactor increasing and decreasing based on adjusting the N_2 atmosphere. The torrefying temperature was set at 200, 250 or 300°C, with a common heating rate of 10°C/min and a residence time of 10, 20, 30, 40 or 50 min. Once the torrefaction process had finished, the oven was cooled under the continual flow of N_2 until the furnace temperature dropped below 100°C.

The torrefaction experiment was performed in a purpose-built horizontal kiln reactor, as shown in Fig. 1. There were four temperature measurement points. The temperature changed as a function of the reaction time during the torrefaction experiment at temperatures below 575°C. A liquid propane gas (LPG) burner was ignited to heat the reactor at 10°C/min. The maximum torrefaction temperature was reached at 105 min and the experiment stopped after 8 hr when no pressure built up had occurred, suggesting the completion of the torrefaction of the PEFB.

Observation of the reactor temperature changes suggested a slow temperature increase (after 72 min of operation, the temperature had just reached 250°C). A notable low heating ramp in the curve was observed, with the reactor reaching a maximum temperature of 575°C after 6 hr. Notably, in the run lasting 450 min, the temperature dropped due to the opening of valves for collecting the liquid products. All temperatures slightly decreased, mostly due to decreased pressure in the LPG tank. The LPG tank supports controlled combustible gas; basically, the nitrogen pressure is regulated to control combustion. The biocoal product was collected and weighed carefully when the reactor reached room temperature. Product distribution based on the torrefaction experiment of PEFB was investigated, suggesting that biocoal was the main product. The yield of gases was calculated by subtracting the weight percentages of the torrefied solid and liquid yields from 100%.

Biomass composition analysis

A portion of the PEFB was characterized according to the methodologies of the National Laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, followed by high-performance liquid chromatography analysis to determine the content of carbohydrate (mostly cellulose and hemicellulose), acid insoluble lignin, acid-soluble lignin, and ash (National Renewable Energy Laboratory, 2012).

Elemental composition (proximate analysis)

The PEFB composition was analyzed using the Materials: 2021 standard method (ASTM E 3174: 2021). The thermogravimetric analysis determined the weight change during thermal decomposition based on ash, volatile matter, and fixed carbon contents. The biomass was crushed to reduce its particle size and passed through a sieve to produce particles smaller than 250 µm. Next, the biomass was dried at 80°C in a hot-air oven for 12 hr. The contents of moisture, volatile matter, fixed carbon, and ash of the biomass were determined based on a thermogravimetric analysis (TGA) technique (no. TA-129).

Elemental composition (ultimate analysis)

The CHNS analyzer (LECO CHN628; LECO; USA) was utilized to determine the PEFB composition of the four major elements (carbon, nitrogen, hydrogen and oxygen) and other elements such as sulfur. Samples were dried at 80°C in a hot-air oven for 12 hr. Fundamental analysis was undertaken of the amounts of carbon, hydrogen, nitrogen, oxygen and sulfur in biomass samples (each 0.05 g). Each sample was placed in foil and wrapped to resemble a drop of water before determination using the elemental analyzer.

Biocoal yield analysis

TGA is recognized as a proven method to determine the thermal decomposition of both raw and torrefied products (Gajera et al., 2022). In this study, the TGA of the raw and torrefied EFB products was performed using a TGA instrument (TGA-50; Shimadzu Corporation; Japan). Approximately 10 mg of the sample was pyrolyzed from room temperature to 900°C at a constant heating rate of 10°C/min. Nitrogen was used as a carrier gas, and its flow rate was controlled for all experiments. The yield of biocoal was calculated using Equation 1:

$$\text{Biocoal yield (\%)} = (W\_Tor / W\_Raw) \times 100\% \quad (1)$$

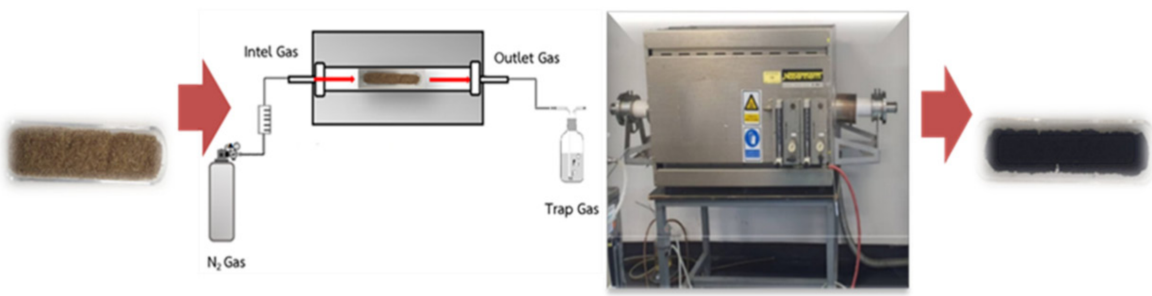

Fig. 1 Composition of horizontal kilns used in the dry-torrefaction process

where W_Raw represents the weight of the biomass before torrefaction, and W_Tor represents the weight of the biomass after torrefaction.

Before the torrefaction process, the biomass was dried at 150°C and kept in a desiccator before weighing. Similarly, the biomass after torrefaction was kept in a desiccator until it had cooled before weighing.

Calorific analysis

The solid fuels' calorific value was analyzed according to the standard test method (ASTM D 240) using a bomb calorimeter. Heat combustion (a measure of the energy available from the biomass) was determined following ASTM (2019). The biomass was crushed until the particles were smaller than 250 µm. The biomass was dried at 80°C in a hot-air oven for 12 hr and then analyzed for calorific value using the bomb calorimeter.

Energy yield analysis

The PEFB biocoal was dehumidified at 80°C in a hot-air oven for 12 hr and then analyzed for calorific value and elemental composition. The approximate components and the yield of solids (hydrochar yield), and the energy yield were calculated.

Process simulation

Generally, the properties of raw materials should be defined based on the data from PEFB characterization. First, this material was categorized as a non-conventional component. Then, the stream class was set as MIXCINC as the components involved in this simulation were a mix of conventional, non-conventional and solid distribution (PSD) of the raw materials and were neglected. During analysis, the RK-SOAVE property method was chosen to calculate the physical properties of the conventional mixed component and the CISOLID components. The HCOALGEN and DCOALIGT models were used to calculate the enthalpy and density of PEFB, respectively.

The PEFB biocoal production process was divided into four sections: 1) pretreatment, where the PEFBs were prepared for feeding into the torrefaction unit; 2) torrefaction, where thermal decomposition of the biomass occurred to produce a high-quality biocoal product; 3) separation, where the quenching method was applied to stop the reaction state and to separate the torrefaction product; and 4) combustion, involving heat recovery to reduce unnecessary energy consumption by combusting the separated char using the torrefaction gas obtained from the separation process. The process flow diagram of the PEFB biocoal production process is proposed. The process equipment can be classified into 11 types: horizontal and vertical vessels, compressors, pumps, heaters, heat exchangers, reactors, screeners, tray dryers, cyclones, and gyratory crushers.

In the first step, PEFB was fed into the pretreatment section for drying and crushing. Next, the dried PEFB was conveyed to the torrefaction section to generate bio-oil, char and gas. Then, the torrefied product was subjected to solid removal and bio-oil recovery to separate the char, bio-oil and gas. Next, the char was combusted using the torrefaction process to upgrade the biocoal to a higher heating value. Finally, the biocoal was used for electricity generation via steam turbines. The simulation used the ASPEN Plus software (Aspen Technology, Inc., 2020a).

Economic evaluation

Investment projects and process optimization aim to maximize financial indicators such as the gross operating margin (GOM) or the net present value (NPV). Maximizing the NPV involves calculating the difference between annual gross profits and total capital expenditure (CAPEX). GOM is the cash flow associated with gross profits and annual operating expenses (OPEX). The purchased equipment cost and direct and indirect costs are included to calculate CAPEX. The current study used the fractionated method to estimate CAPEX based on equipment costs, which were estimated using the Aspen Process Economic Analyzer (APEA). The Marshall & Swift Equipment Cost Index was used to value the purchased equipment involved in determining the 2017 and 2023 values. OPEX was estimated using the summation of direct costs, fixed costs and general expenses. This study utilized the fractionated OPEX calculation (Peters et al., 2003). The discounted flow rate was used to apply an adjustment factor to the NPV. The adjustment factor (the weighted average capital cost at 7%) was used to discount future cash flow for new investments. The ethanol production operation was set at 7,200 hr. A summary of the economic analysis parameters and their assumed values is provided in Table 1. These assumptions were based on the APEC database for ordinary plants (Aspen Technology, Inc., 2020b).

Table 1 Additional assumptions used in economic evaluation

Parameter	Value
Number of periods for analysis	20 yr
Number of operating weeks	52 wk/period
Number of operating hours	7,200 hr/period
Plant lifetime	20 yr
Required rate of return	10%
Tax rate	10%
Working capital	5%
Depreciation method	Straight line
Salvage value	10% of purchased equipment cost
Weighted average capital cost	7%

Results and Discussion

Experiment results

The yields of bio-oil in the torrefaction simulation of PEFB with variations in the temperature composition are shown in Table 2. In general, the yield of pyrolytic oil decreases as the temperature increases (Mamvura et al., 2018). Based on the proximate analysis data, PEFB had a high volatile matter content. Notably, modeling the torrefaction process applied the chemical reactions associated with the compounds in the biomass (cellulose, hemicellulose and lignin). However, pyrolytic oil consists of hundreds of organic compounds; therefore, proposing a model for all the compounds involved in this reaction would not be practicable (Ansari et al., 2019).

The physical properties of the PEFB samples were assessed initially to determine the contents of water, ash, volatile matter, and fixed carbon. Then, the chemical composition was analyzed to set the properties during the simulation process. These analyses were done on an air-dried basis. The results of the proximate and ultimate analyses of the PEFB are shown in Table 2. In general, PEFB contained more volatile matter than fixed carbon. However, PEFB had a high fixed carbon content and relatively low ash content. Additionally, the volatile matter content of PEFB was the highest, accounting for 60–75% at the same temperature and residue time. Furthermore, the ultimate analysis results at 300°C indicated that the carbon content in the PEFB sample was slightly higher. These findings suggested that the production of biocoal from PEFB would be viable. In addition, based on the results, the yield of biocoal from PEFB at 300°C and a residue time of 30 min was 56.13%, which was higher than the bio-oil yields obtained from the PEFB biomass feedstocks. This result suggested that PEFB would be a promising feedstock for producing biocoal.

Table 2 Torrefaction product distribution, proximate composition, calorific value and energy yield of palm empty fruit bunch (PEFB) samples at different temperatures

Standard order	PEFB sample		Relative amount (yield wt%)				Product ratio (yield wt%)			% Solid yield (%w/w)	Net calorific value (MJ/kg)	%C	%H	%N	Ash (%w/w)	% Energy yield	% Energy density
	Temp (°C)	Time (min)	Volatile matter	Ash	Fixed carbon	Moisture content	Solid	Liquid	Gas								
1	250.0	51.2	62.01	2.73 ± 0.12	32.68	4.90	32.68	5.31	62.01	54.98	20.92 ± 0.16	54.67 ± 0.15	5.75 ± 0.04	0.77 ± 0.35	2.73 ± 0.00	69.24	1.26
2	320.7	30.0	34.08	5.14 ± 0.10	61.57	4.33	61.57	4.35	34.08	31.21	26.20 ± 0.32	68.39 ± 0.32	4.63 ± 0.25	1.28 ± 0.09	5.14 ± 0.00	49.23	1.58
3	250.0	30.0	58.63	2.24 ± 0.24	30.06	5.44	30.06	11.31	58.63	61.39	20.95 ± 0.26	54.41 ± 0.09	6.05 ± 0.47	0.91 ± 0.03	2.24 ± 0.00	77.43	1.26
4	250.0	30.0	62.89	2.39 ± 0.06	31.35	5.03	31.35	5.76	62.89	62.55	20.65 ± 0.30	53.98 ± 0.16	5.79 ± 0.03	0.92 ± 0.03	2.39 ± 0.00	77.73	1.24
5	250.0	30.0	62.40	2.61 ± 0.08	31.91	3.08	31.91	5.69	62.40	59.13	21.48 ± 0.09	56.13 ± 0.27	5.61 ± 0.01	1.03 ± 0.07	2.61 ± 0.00	76.43	1.29
6	200.0	15.0	75.44	1.87 ± 0.05	20.30	4.09	20.30	4.26	75.44	87.50	18.50 ± 0.40	48.68 ± 0.20	6.21 ± 0.27	0.66 ± 0.04	1.87 ± 0.00	97.44	1.11
7	200.0	45.0	72.31	2.22 ± 0.22	23.37	3.96	23.37	4.32	72.31	78.93	19.38 ± 0.30	50.99 ± 0.51	6.17 ± 0.13	0.86 ± 0.05	2.22 ± 0.00	92.07	1.17
8	250.0	30.0	61.41	2.88 ± 0.04	32.50	5.47	32.50	6.09	61.41	60.91	21.52 ± 0.20	55.51 ± 0.10	5.74 ± 0.02	1.01 ± 0.10	2.88 ± 0.00	78.90	1.30
9	300.0	15.0	34.78	5.49 ± 0.15	55.89	5.89	55.89	9.33	34.78	33.67	27.20 ± 0.14	69.28 ± 0.43	4.70 ± 0.04	1.49 ± 0.09	5.49 ± 0.00	55.11	1.64
10	300.0	45.0	31.78	5.83 ± 0.26	56.13	6.26	56.13	12.09	31.78	32.21	26.93 ± 0.11	70.25 ± 0.41	4.44 ± 0.02	1.53 ± 0.02	5.83 ± 0.00	52.21	1.62
11	179.3	30.0	78.28	1.78 ± 0.03	17.65	4.50	17.65	4.07	78.28	90.66	18.21 ± 0.13	48.63 ± 0.10	5.73 ± 0.01	0.86 ± 0.03	1.78 ± 0.00	99.37	1.10

Note: ± Confidential range from - to + with the number indicated.

Thermogravimetric analysis (TGA)

The TGA and Differential Thermogravimetric Analysis (DTG) curves indicated that the thermal decomposition rate of PEFB consisted of three main phases: dehydration, devolatilization and lignin decomposition as was also reported by Al-Rahbi et al. (2016). Within the dehydration phase (from room temperature to 180°C), 12% of the sample mass was lost, due to the removal of the water molecules retained in the pores of the biomass and the removal of some very light volatiles. The second stage of PEFB decomposition occurred in the range 180–400°C, generally due to the devolatilization of volatile matter. It has been suggested that the carbohydrate-rich volatile fraction of organic matter decomposes within the range 190–300 °C, followed by organic polymer fractions rich in lipids at up to 350°C (Waters et al., 2017). Most of the volatile fractions reportedly decomposed at 400 °C, after which the devolatilization rate decreased rapidly (Bindar, 2013). In the current study, the third phase occurred in the range 400–900°C and involved the decomposition of the less-biodegradable proteins, lignin and synthetic organic polymers. The maximum rates of dehydration and devolatilization occurred at 66°C and 347°C, respectively. The TGA and DTG profiles showed that the primary weight loss during the combustion of the raw and torrefied biomass occurred due to the thermal and oxidative degradation of the biomass. The hemicellulose and cellulose components decomposed within the range 250–410°C, while lignin decomposed in the range 410–620°C. The PEFB biomass torrefied at 250°C and 300°C had maximum weight loss under air combustion at approximately 370°C. There was a good correlation between the PEFB yield and temperature at 300–320°C, suggesting that this temperature range exhausted the yield of PEFB, making it a suitable biomass material for making biocoal.

Temperature profile and product distribution of torrefaction experiment

Some portions of the PEFB were removed during the subcritical temperature pretreatment process. At the same time, solid residue remained, which was mainly composed of cellulose and a minor content of residual hemicellulose and lignin. The mean ± standard deviation calorific value (CV) calculated from Equation 2 ranged from 26.10 ± 0.32 to 18.21 ± 0.13 MJ/kg.

$$CV = 26.1 - 0.1209Temp + 0.080Time + 0.000402Temp^2 + 0.00054Time^2 - 0.000383Temp \times Time \quad (2)$$

Fig. 2 shows the three-dimensional response surface for CV at fixed central point values for the wt% PEFB. PEFB processing was fixed at reaction times of 15–50 min and reaction temperatures in the range 200–320°C. Increasing the reaction temperature led to an increase in the CV. For example, increasing the reaction temperature in the experiment from 200°C to 320°C increased the CV (from 26.10 ± 0.32 to 18.21 ± 0.13 MJ/kg).

Some portions of the PEFB were removed during the sub-critical temperature pretreatment process. At the same time, solid residue, mainly composed of cellulose and a minor content of residual hemicellulose and lignin, remained. As a result, the energy yield calculated from Equation 3 was in the range of 99.37 to 49.23%.

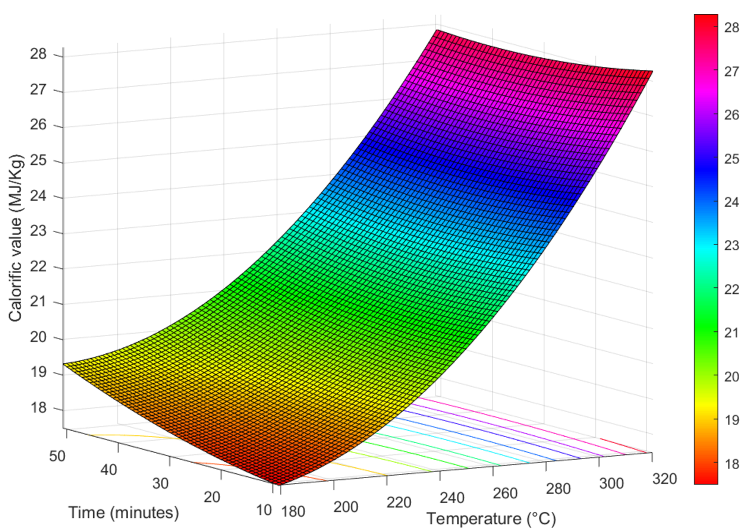

Fig. 2 Calorific values versus time and temperature

$$\text{Energy yield} = 139.9 - 0.047\text{Temp} - 0.349\text{Time} - 0.000721\text{Temp}^2 - 0.00184\text{Time}^2 + 0.00082\text{Temp} \times \text{Time} \quad (3)$$

Fig. 3 shows the three-dimensional response surface for the % energy yield at the fixed central point values for wt% PEFB. PEFB processing was fixed with reaction times of 15–50 min and reaction temperatures of 200–320°C. Increasing the reaction temperature led to a decrease in the energy yield. For example, increasing the reaction temperature in the experiment from 200°C to 320°C resulted in a decrease in the energy yield from 99.37% to 49.23%.

Simulation results

Assessing the amount of energy obtained from PEFB combustion and the production process requires measuring the calorific value and energy yield of biocoal. These two measures are correlated but not directly related, as torrefaction conditions and recovery methods for byproducts. The chemical composition of PEFB can influence energy yield, while the chemical composition of the feedstock primarily determines the calorific value. However, notably, various factors, such as feedstock composition, operating conditions and process design, can impact biocoal yield. The simulation results should always validate the actual yield from a pilot-scale production plant. The current research supported PEFB's potential for making biocoal under torrefaction conditions based on the calorific value and energy yield information from the experimental results.

Table 3 presents the properties of PEFB based on the experiments in which the PEFB was utilized in various applications as a raw material for the torrefaction process. The current study conducted the torrefaction process using a fixed feeding rate of 78,177.40 kg/hr PEFB to produce biocoal. The fluidized bed reactor operated at 300°C and 1.2 bar, while the combustor operated at 1,296°C and 1 bar. The operating conditions of the steam turbine varied based on the heat energy produced from combustion.

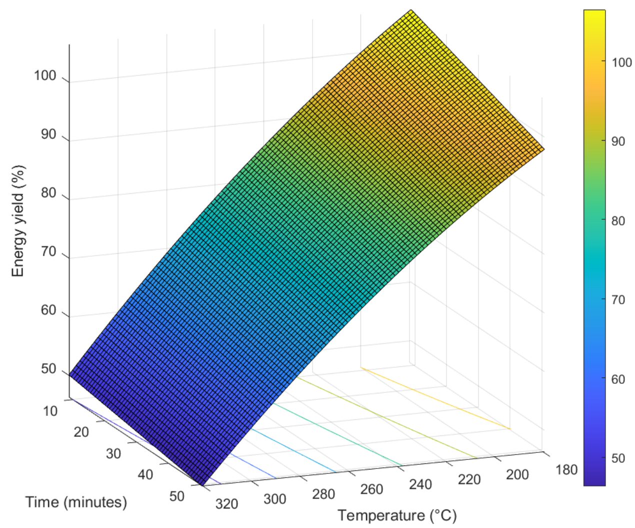

Fig. 3 Energy yields versus time and temperature.

Table 3 Proximate and ultimate properties of palm empty fruit bunches (air-dried)

Proximate composition (%wt.)		Ultimate composition (%wt.)		Biomass composition (%wt.)	
Moisture	6.04	Carbon atoms	47.01	Cellulose	59.7
Fixed carbon	21.45	Hydrogen atoms	5.70	Hemicellulose	22.1
Volatile matter	71.48	Oxygen atoms	45.87	Lignin	18.1
Ash	1.03	Nitrogen atoms	0.30		
		Sulfur atoms	0.09		
		Ash	1.03		

%wt. = weight on a percentage basis.

Fig. 4 shows the simulation results of biocoal production following upgrading with a heat exchanger network design. The PEFB was fed into the process at a mass flow rate of 78,177.40 kg/hr or 1728 t/day. The first step involved pre-treating the PEFB to reduce its size to about 3 mm and then drying it to less than 10% moisture content at 105°C. The reactor (CSTR) was operated at 300°C and a residence time of 30 min; these conditions were suitable for producing biocoal via the torrefaction process, as derived from the experimental study. The torrefaction model used 149 kinetic equations to decompose PEFB into char, gas and bio-oil (Peters et al., 2017). Then, a cyclone separator was used to separate the biocoal. The volatile product was a direct mixed bio-oil stream quenched to 100°C and 45°C to separate the bio-oil and biogas. Finally, the biocoal was used to generate electricity. The combustor was modeled as two reactors (RYield and RGibbs) that calculated heat balance and combustion products based on Gibbs energy minimization. The biocoal yields were adjusted to an oxygen content of less than 2% using high hydrogen pressure at 1.2 bar. Cyclone separation produced char, fly ash and bottom ash residue. The hydrocracker was developed in ASPEN Plus using RStoic (Tumuluru et al., 2011). The heat exchanger network was used to minimize the energy consumption of the process, where the best design was selected based on the lowest total cost (Junsittiwate et al., 2022). In this simulation, torrefaction was performed at 300°C and the resulting product yields were compared to the TGA data. The purpose of the experiment was to investigate the impact of various characteristics of the raw material on product yield.

The simulation of the PEFB mixture at 300 °C showed a decrease in bio-char production with increasing temperature due to faster devolatilization and a reduction in carbon levels (Han et al., 2023). This trend was consistent with the proximate analysis results that indicated a higher ash content and lower volatile matter content in the PEFB. The literature reported a decrease in the pyrolytic oil yield with increasing temperature, which was consistent with the current simulation results (Peters et al., 2017). In addition, the high volatile matter content in the PEFB resulted in higher pyrolytic oil production, which was in line with another study (Adeniyi et al., 2019). However, modeling all the organic compounds involved in the torrefaction reaction was impractical due to the numerous compounds present in pyrolytic oil. The simulation generated results of 78,177.40 kg/hr or 1,876.25 t of PEFB per day at 300°C, producing 21,631.70 kg/hr of char, 14,530.29 kg/hr of gas, 1,279.31 kg/hr of bio-oil and 40,736.10 kg/hr of vapor, which were consistent with another study (Peters et al., 2017). Furthermore, the simulation indicated levels of CO_2 emissions, electricity utility and water supply of 40,386.90 kg/hr, 270.03 kW/hr and 1,099.97 L t/hr, respectively, suggesting a suitable process model. The optimal biocoal yield and utility cost were 21,631.70 kg/hr and USD 4.06 million, respectively, with a 20-yr life cycle and a total capital investment of USD 20.38 million. The primary focus was on evaluating the economic feasibility of producing biocoal. The first step involved calculating the equipment size and estimating the associated purchase cost. The major equipment, such as the pump, heat exchanger, reactor and distillation column were sized. The costs were estimated using APEA. However, the equipment

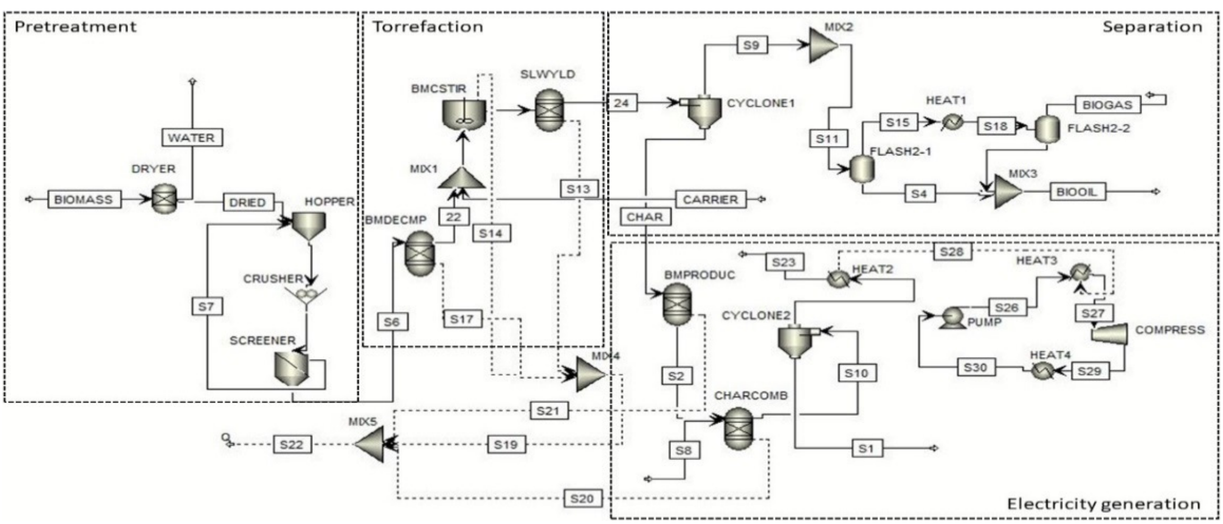

Fig. 4 Biocoal production process simulation of PEFB.

was sized for batch units based on mass flow through the units using a cycle time. Purchased costs for equipment that were not provided by Aspen Process Economy Analyzer were estimated using the unit's capacity as a characteristic (Chrisandina et al., 2019).

Several factors could have contributed to the differences between the biocoal yield from the actual pilot plant and the experimental, laboratory-scale study, including differences in the equipment and processes used (such as variations in the heating rate, temperature and residence time, which can affect the yield) and variations in the feedstock used that could have a major impact, as some feedstocks may be more conducive to biocoal production than others. In addition, the environment in the pilot plant could differ from that in the laboratory-scale study, (such as variations in humidity and temperature affecting the biocoal yield). Scaling up from the laboratory scale to a pilot plant scale could introduce several factors affecting biocoal yield, including the increased difficulty in controlling variables, such as the heating rate and temperature. Finally, operator skill and experience differences may also play a role, leading to variations in how the biocoal is produced. Identifying and addressing these factors would be essential to improve the consistency and efficiency of biocoal production.

Conclusion

Based on the simulation of a PEFB mixture at 300°C, the production of biocoal decreased with increasing temperature due to faster devolatilization and a reduction in carbon levels. An experimental result was used to adjust the model of torrefaction. Subsequently, the conception design was completed and economic considerations were studied.

PEFB agro-industry residues were experimentally investigated and simulated using the Aspen Plus software and a steady-state thermodynamic model. The study used PEFB at temperatures in the range 200–300 °C. The experimental results from the PEFB decomposition at varying temperatures based on the results from the Aspen Plus simulation were supported by the TGA and DTG results. The thermal decomposition rate of PEFB could be divided into three phases: dehydration, devolatilization and lignin decomposition. The dehydration phase resulted in a 12% loss of sample mass due to the removal of water molecules and light volatiles. The optimal biocoal yield and utility cost were 21,631.70 kg/hr and USD 4.06 million, respectively, with a 20-yr life cycle and a total capital investment of USD 20.38 million.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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