APTEFF, 53, 1-302 (2022) UDC: 66.011:635.054:661.635.41
DOI: https://doi.org/10.2298/APT2253109O BIBLID: 1450-7188 (2022) 53, 109-122
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OPTIMIZATION OF HHV AND ENERGY YIELD FROM TORREFACTION OF *ALBIZIA ZYGIA* WOOD- CALCIUM HYDROGEN PHOSPHATE CATALYST BLENDS USING OPTIMAL COMBINED DESIGN

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Received: 15 April 2022 **Revised: 16 June 2022** **Accepted: 20 June 2022**

The over-reliance on fossil fuels as a primary source of energy is partly responsible for the increase in carbon dioxide (CO2), depletion of the ozone layer, and general environmental pollution. In this study, torrefaction of Albizia zygia wood-calcium hydrogen phosphate ($CaHPO_4$) catalyst blends was carried out in a tubular furnace to examine the impacts of temperature, time, and particle size on higher heating value (HHV) and energy yield (EY). Albizia zygia wood was obtained at an industrial sawmill junkyard nearby Kwara State University, dried, crushed, and sieved into 1 – 3 mm particle size. Optimal Combined Design (OCD) was employed for the design, modelling, and optimization of HHV and EY under the ranges of selected temperature (200 – 300 °C), residence time (15 – 30 min), and particle size (1 – 3 mm) in an inert environment tubular furnace. The results of the analysis indicated that the temperature of 245 °C, time of 22 min, and size of the particle 3 mm yielded a maximum HHV of 19.59 MJ/Kg and EY of 76.37% respectively. Also, the addition of catalyst ($CaHPO_4$) at 10% reduced the ash content but enhanced the fixed carbon content of the biochar. The mathematical models for the HHV and EY for the torrefaction using the OCD imply an excellent fit with R^2 of 0.92 and 0.96, respectively. The prediction accuracy indicates that OCD can be deployed for the accurate prediction of HHV and EY in torrified biomass.

Keywords: optimization, *Albizia zygia*, calcium hydrogen phosphate, energy yield, torrefaction, HHV.

INTRODUCTION

The demand for energy and the cost of fossil-derived fuels are rising due to population growth, increased standard of living, and technological advancement (1). Fossil fuel-based energy comes with harmful environmental effects such as greenhouse gases (GHG) and subsequent global warming (2). In order to mitigate these challenges, the United Nations Climate Change aims at limiting the rise in global temperature to not more than 2 ℃ (3). To achieve this objective, the advancement of renewable energy for instance biomass, hydropower, wind, and solar energy is now given sufficient attention owing to their abundance as well as ecological friendliness (4).

Biomass, obtainable from plant and animal sources, is an alternative source of carbon-based solid fuel that can reduce the reliance on fossil fuels as well as ameliorate global warming and other ecological challenges related to the application of fossil fuels (5). Sawdust is an organic residue abundant in Nigeria and is often found in sawmills as waste with

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no economic value (6,7). Burning *Albizia* wood sawdust releases massive amounts of toxic gases and aerosol particles into the environment, posing a serious threat to the quality of air, human health, and environmental issues (4).

Biochar is a solid fuel with a high carbon content that can be produced from plant-based biomass such as rice husk, bamboo sawdust (8), sugarcane bagasse (9), teak sawdust (10), cotton shell (11), palm kernel shell (12), among others. The yield of the biochar is dependent on the reaction time, process temperature, particle size, and heating rate in the course of the torrefaction method (13). The versatility of biochar in agricultural and environmental sectors has garnered enormous attention due to its unique properties like minimal bulk density, higher porosity, poor thermal conductivity, high stable structure, and larger surface area (14).

Torrefaction is a process that involves the thermal pretreatment of biomass in an oxygen-limited medium at temperatures ranging from 200 to 300 °C (15). This process is a mild pyrolysis treatment that is performed in a nonreactive environment to enhance the physicochemical properties of the biomass (9). The process is more economical and ecofriendlier than gasification and pyrolysis. In addition, the operating temperature limits are higher and more energy is expended during the pyrolysis and gasification process (16).

Design of Experiment (DoE) is a strong data gathering and analysis technique that may be applied to a wide range of experimental circumstances. DoE facilitates the manipulation of many input components and the determination of their relationship with the desired outcome. In the various methodology of DoE version 12.0 such as factorial, response surface, mixture, and custom design. Custom design methodology combines both the mixture components and factor, and the measured response depends on both the relative ratio of the mixture components and the factor (25). Optimal Combined Design (OCD) is not orthogonal like that of the two classic response surface designs (Central Composite (CCD) and Box-Behnken (BBD)). The major feature of OCD is that it can be used to fit any kind of model or mathematical equation which can be first and second order, full quadratic, and cubic. It is also applicable for any research goal, such as screening or generating a response surface. However, Second-order designs such as CCD and BBD determine the curvature interaction among the parameters and express it as a quadratic equation. In addition, compared to the classic type, OCD allows for fewer experimental trials and a smaller design space (17).

The inclusion of a catalyst in the torrefaction method has also been studied for various biomass sources (18). The use of catalysts during the pyrolysis process changes the degradation tendency of biomass as well as the compositions and quantities of pyrolysis products. ZSM-5 zeolites were discovered to be efficient in increasing the deoxygenated aromatic composition of pyrolysis products despite decreasing liquid yields (19). The use of silica-alumina with or without alkali metal deposition promotes water formation and boosts gas and char yield, as well as decreases the total organic yield when compared to traditional pyrolysis. (20).

Catalysts also influence the distribution and composition of chemical components in pyrolysis products. Acidic-based catalysts such as NaOH and KOH have a limitation in forming soap due to the higher content of fatty acids in the feedstock (21). Calcium hydrogen phosphate ($CaHPO_4$) is a green, mild, effective, cheap, and ecologically friendly catalyst (22). It is beneficial in reducing carbon loss during pyrolysis, enhancing carbon retention of the biomass, and strengthening biochar stabilization (34). Levoglucosan yields

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were reduced significantly when cellulose was treated with inorganic salts like $CaHPO_4$. This reduction in levoglucosan yields is caused by the catalytic reactivity of additional metal salts, which increases char production and decreases ash formation. The phosphate can usually aggravate the dehydration reaction of biomass, and hinder the production of Levoglucosan. The phosphate promotes the production of thermally stable metaphosphates, which act as a physical barrier or hinder the active site of the carbon to inhibit the oxidative decomposition of biochar (35).

The inert nitrogen gas, heat transfer to the pyrolysis system, particle size, reaction time, and catalyst are the factors that influenced the pyrolysis of the biomass. These factors influenced the yield, product distribution, as well as capacity to produce methane, bio-oil, and biochar with higher heating values (23). Optimization of these parameters can enhance the scale-up of the reactor, economy, and efficiency of the system. This can be done using the Custom Design Methodology which has been deployed to optimize various processes in engineering because of its versatility, time, and energy saving (24). To the best of our knowledge, torrefaction of sawdust of *Albizia zygia* wood using $CaHPO_4$-catalyst for the production of biochar has not been reported. This study, therefore, reports the optimization of HHV and EY from the torrefaction of the sawdust-catalyst mixture.

MATERIALS AND METHODS

PREPARATION OF MATERIALS

The sawdust was obtained from an industrial sawmill dump nearby Kwara State University, Nigeria. The sample was crushed using a granulator (SG-16 Series) and sieved with a sieve shaker of 1-3mm diameter sieve size for uniform distribution of the sample. The impurities in the sawdust were eliminated by cleaning the selected biomass thrice with distilled water via sedimentation. The impurities and heavy solid particles settled down in the distilled water because sand and other particles are denser than water whereas the sawdust (which has a lower density than water) floated on the water. The sawdust was then skimmed off and further separated from the water via the filtration process. Subsequently, the sample was sundried for seven (7) days and further dried in the Gallenkamp dry oven at the temperature of 105 °C. In line with ASTM 3173-87, the drying was completed until a consistent weight was achieved (5). The catalyst used for this research was $CaHPO_4$ and was obtained from a representative of the manufacturer in Nigeria.

EXPERIMENTAL DESIGN

OCD under the Custom Design Methodology (Design-Expert software version 12.0.1.0) was used to optimize the proportion of the sawdust and $CaHPO_4$, and process factors (temperature, particle size, and residence time). The minimum and maximum levels of the component mixture were 0 and 100% respectively while factors including temperature (200-300 °C), particle size (1-3 mm), and residence time (15-30 min) are the process parameters (Table 1). The range of the particle sizes was selected because smaller particles promote heat and mass transfer to keep the relatively constant temperature within them during the degradation of the biomass. This study also focused on the torrefaction of sawdust with short intervals of residence duration. OCD was employed to identify the relationship bet-

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ween the components of the mixture and factors with the response functions. These ranges were input into Design-Expert software and then generated 35 experimental Runs (Table 2) which mixed the biomass and catalyst in various percentages aggregating to 100% and at each experimental run for the different temperature, residence time, and particle size.

Table 1. The level of the proportion of the mixture and process factors for OCD

Levels	Component Mixture		Factors		
	Sawdust (wt.%)	$CaHPO_4$ (wt.%)	Temperature (°C)	Particle (mm)	Time (min)
Minimum value	90	5	200	1	15
Maximum value	95	10	300	3	30

EXPERIMENTAL PROCEDURE

Torrefaction of sawdust blends with calcium hydrogen phosphate was conducted in an electrically powered tubular furnace (Model YTF-40-12) with the heating element of Kanthal A1 as the heat source. The experimental setup is shown in Figure 1. Each experimental run was carried out based on the data provided in Table 2. The temperatures and residence time were set after the crucible with the sample of 10g was carefully laid inside the furnace. The torrefaction process was done in a nonreactive environment by supplying nitrogen gas with a flow rate of 3 mL/min into the tube furnace. This was necessary to avert the combustion of the biomass. The furnace was switched off when the set temperature and time for each experimental run were reached. The biochar was cooled to a temperature of 25 ± 1 °C and the resulting biochar was dried and weighed. The mass yield (MY), energy density (ED), and enhancement factor (EF) were estimated according to Equations 1, 2, and 3, respectively. All analyses involved in the torrefaction of sawdust-$CaHPO_4$ mixture under varied process parameters were conducted in triplicate to ensure accurate results and their average values were recorded.

$$MY = \frac{m_{bc}}{m_{bm}} \times 100 \quad [1]$$

$$EF = \frac{HHV_{bc}}{HHV_{bm}} \quad [2]$$

$$EY = EF \times MY \quad [3]$$

where m_{bc} is the mass of the dried biochar, m_{bm} is the mass of the dried biomass, and HHV_{bc} and HHV_{bm} is the higher heating value of the dried biochar and dried biomass respectively.

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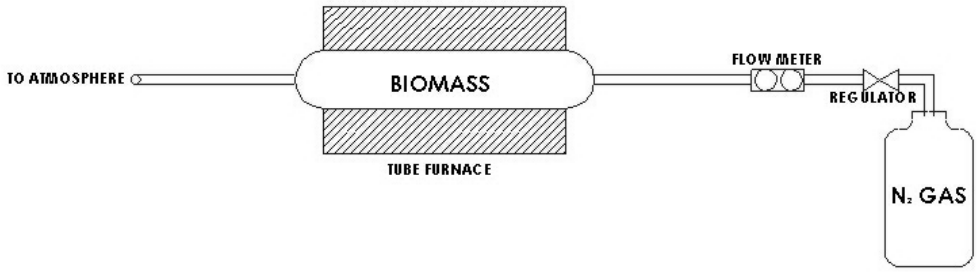


Figure 1. Experimental setup for torrefaction process.

CHARACTERIZATION OF THE FEEDSTOCK AND PRODUCTS

The proximate and ultimate analyses were conducted on the sawdust and the torrefied sample at optimum conditions. The ultimate analysis was done by using CHNS elemental analyser (Perkin Elmer N2410650 Series II 100V) to determine the chemical composition of the biomass and torrefied samples with optimal parameters following ASTM D5373-93. The oxygen content was calculated by subtracting 100 from the total percent of CHNS. The proximate analysis was done according to the ASTM E870-82 standards. The calorific or heating values of the samples were evaluated using the Gallenkamp ballistic bomb calorimeter according to ASTM D-5865 (3).

STATISTICAL ANALYSIS

The responses of the torrefaction process (MY, HHV, and EY) were investigated statistically using analysis of variance (ANOVA) which was incorporated in the DoE Software version (12.0.1.0). These analyses were conducted to determine the fitness of the models produced using coefficients of determination (R^2), and the mean square errors (MSE) (25).

RESULTS AND DISCUSSIONS

OPTIMAL COMBINED DESIGN AND STATISTICAL ANALYSIS

The experimental and corresponding predicted values for each experimental run are presented in Table 2. The optimal process conditions to produce torrefied biomass were determined from the experimental runs with maximum HHV using Table 2. Thus, the optimal process conditions for the maximum EY (76.37%) and HHV (19.59 MJ/Kg) were 90% of sawdust, 10% catalyst, the temperature of 245 °C, the residence time of 22 mins, and particle size of 3 mm. Regression analysis was used to determine the correlation between the independent parameters (temperature, residence time, and particle size) and the dependent variables (EY and HHV). The derived models for predicting the EY and HHV as a function of sawdust, $CaHPO_4$, temperature, residence time, and particle size as obtained from the Design-Expert version 12.0 are provided in Equations 4 and 5, respectively. The relationship between the experimental and forecasted values for EY and HHV are presented in

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Figures 2 (a and b) correspondingly. There was good agreement and consistency between the datasets of the experimental and predicted values. This affirmed the accuracy of the reported model and its usefulness for predicting the EY and HHV (26).

EY = -1.94594A - 1123.43428B + 12.91919AB - 0.019122AC + 1.03996AD - 4.68420AE + 1.09886BC + 149.87820BD - 385.99445BE - 0.010782ABC - 1.76992ABD + 4.65146ABE - 0.003391ACD + 0.033508ACE - 0.113573ADE - 0.494215BCD + 3.43658BCE - 17.52501BDE + 0.005825ABCD - 0.041194ABCE + 0.206808ABDE [4]

HHV= 14.72437A - 30838.97883B + 497.07534AB - 0.070944AC + 0.241200AD - 1.99741AE + 148.54141BC - 489.36849BD + 4240.40268BE - 2.39493ABC + 7.89579ABD - 68.35317ABE - 1.94839AB(A - B) + 0.009395ABC(A - B) - 0.031030ABD(A - B) + 0.267962ABE(A - B) [5]

where A = Sawdust, B = $CaHPO_4$, C = temperature, D = residence time, and E = particle size.

Table 2. Experimental studies and responses based on OCD

Run	Components		Factors			MY	EY (%)			HHV (MJ/Kg)		
	A (%)	B (%)	C (°C)	D (min)	E (mm)	(%)	Actual	Predicted	Difference	Actual	Predicted	Difference
1	95	5	300	24	3	38.33	44.75	46.56	-1.81	18.32	18.32	0.0002
2	95	5	300	30	1	37.56	46.59	48.97	-2.38	19.46	19.45	0.0084
3	95	5	200	30	3	51.66	64.17	67.39	-3.22	18.43	18.49	-0.0558
4	90	10	300	30	1	41.43	48.66	48.97	-0.3053	19.49	19.44	0.0522
5	91	9	200	30	2	40.37	49.76	69.96	-20.2	19.34	19.14	0.1982
6	93	7	300	21	3	35.93	42.53	47.61	-5.08	18.57	18.46	0.113
7	90	10	287	23	1	47.75	56.39	61.78	-5.39	18.53	18.52	0.0141
8	92	8	300	15	2	37.83	44.70	41.91	2.79	18.54	18.60	-0.056
9	90	10	300	15	3	37.22	44.72	44.37	0.35	18.85	18.71	0.1446
10	90	10	299	22	2	39.78	46.50	48.43	-1.93	18.34	18.43	-0.0865
11	92	8	200	15	1	42.73	53.00	57.94	-4.94	18.60	18.46	0.1351
12	90	10	300	30	3	35.17	43.06	40.38	2.68	19.52	19.54	-0.0212
13	92	8	262	24	2	58.73	73.03	73.79	-0.7551	19.51	19.54	-0.0305
14	92	8	238	30	3	64.95	77.00	74.75	2.25	18.60	18.50	0.1027
15	90	10	245	30	2	58.65	73.00	77.13	-4.13	19.53	19.57	-0.0432
16	90	10	263	15	1	49.10	61.02	64.39	-3.37	19.50	19.52	-0.0153
17	90	10	234	20	2	61.13	75.00	77.21	-2.21	19.25	19.23	0.0166
18	95	5	200	30	1	67.26	79.00	74.22	4.78	18.43	18.33	0.097
19	92	8	300	15	1	36.30	43.03	40.57	2.46	19.46	19.51	-0.0466
20	92	8	200	30	1	69.37	81.00	74.22	6.78	18.32	18.33	-0.014
21	90	10	200	24	1	59.83	71.00	72.90	-1.9	18.62	18.77	-0.1486
22	92	8	202	23	2	62.05	77.00	70.89	6.11	19.47	19.34	0.1261
23	95	5	202	22	2	66.39	79.00	69.92	9.08	18.67	18.67	-0.0021
24	93	7	255	23	1	61.95	77.03	78.25	-1.22	19.51	19.53	-0.0192
25	95	5	255	30	2	57.09	71.02	73.73	-2.71	19.52	19.52	0.0039
26	95	5	200	15	1	49.50	59.00	57.94	1.06	18.70	18.81	-0.1128
27	95	5	300	15	2	33.48	39.07	40.95	-1.88	18.31	18.33	-0.0233
28	90	10	200	15	2	49.83	58.25	60.40	-2.15	18.34	18.33	0.0133
29	92	8	200	15	3	48.61	60.42	63.50	-3.08	18.50	18.54	-0.0422
30	92	8	255	15	2	66.80	78.12	68.83	9.29	18.35	18.50	-0.1535
31	95	5	255	22	1	69.01	73.09	77.09	4	18.89	19.01	-0.1193
32	95	5	237	15	3	62.62	74.12	73.81	0.3114	18.57	18.70	-0.1323
33	90	10	200	30	3	60.86	75.71	67.39	8.32	19.21	19.16	0.0544
34	90	10	245	22	3	61.35	76.37	78.42	-2.05	19.59	19.51	0.0800
35	93	7	300	30	2	43.13	53.05	44.63	8.42	19.30	19.28	0.0206

A - Sawdust, B - $CaHPO_4$, C - temperature, D - residence time, E - particle size

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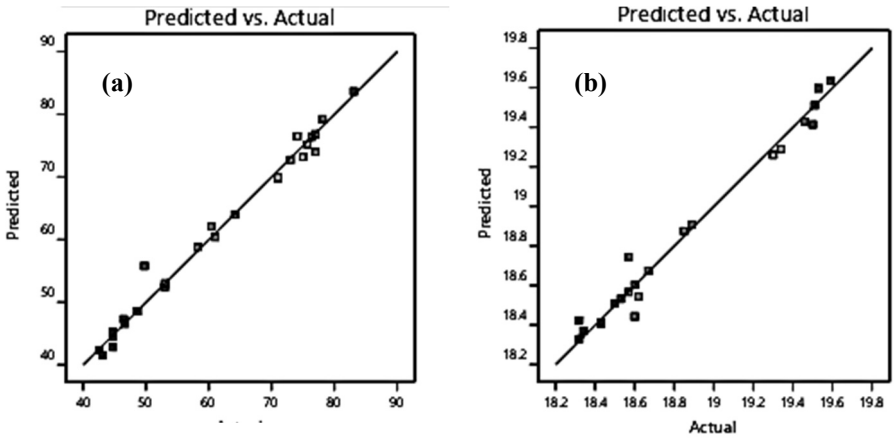


Figure 2. Relationship between the experimental and predicted values of **(a)** EY and **(b)** HHV.

At a 95% confidence level (Table 3) the terms in the equations are said to be significant when the p-value is less than 0.5. In this case, AB, AC, and ABD are significant for HHV yield with strong interaction, for EY yield, the most significant terms are AC, AE, ACE and BCE. The model F value of 3.35 and 16.78 for HHV and EY implies the model is significant. Additionally, the standard deviation (0.77 and 0.65 for HHV and EY yield, respectively), coefficient of determination R^2 (0.92 and 0.96), R^2_{Adj} (0.85 and 0.93), and other parameters backed the accuracy and adequacy of the models.

EFFECTS OF CATALYST ON EY AND HHV OF THE TORREFIED BIOMASS

Torrefaction of sawdust with $CaHPO_4$ catalyst under varied process parameters was examined as shown in Figure 3. The effect of the catalyst during torrefaction shows that the MY, EY, and HHV of the torrefied biomass increased as the percentage composition of the catalyst increased under the same process parameters as shown in Figure 3. The MY, EY, and HHV of the biochar produced from the feedstock with sawdust of 95% and 5% of $CaHPO_4$ improved from 37.56% to 41.43%, 46.59% to 48.66%, and 19.46 MJ/Kg to 19.49 MJ/Kg respectively while compared with the feedstock of sawdust (90%) and $CaHPO_4$ (10%). Both feedstocks were subjected to torrefaction at the temperature of 300 °C, the residence time of 30 min, and particle size of 1 mm.

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Table 2. ANOVA analysis for the HHV AND EY

Source	Sum of Squares	Df	Mean Square	F-value	P-value
HHV					
Model	3.95	15	0.2636	3.35	0.0296*
Linear Mixture	0.3022	1	0.3022	3.84	0.0785*
AB	0.0872	1	0.0872	1.11	0.0317*
AC	0.9425	1	0.9425	11.98	0.0061*
AD	0.0839	1	0.0839	1.07	0.0326*
AE	0.0618	1	0.0618	0.7854	0.3963
BC	0.0316	1	0.0316	0.4017	0.0540*
BD	0.2381	1	0.2381	3.03	0.0126*
BE	0.2262	1	0.2262	2.87	0.1208
ABC	0.1017	1	0.1017	1.29	0.0282*
ABD	1.90	1	1.90	24.16	0.0006*
ABE	0.0277	1	0.0277	0.3521	0.5661
AB(A-B)	0.1200	1	0.1200	1.52	0.2452
ABC(A-B)	0.3819	1	0.3819	4.85	0.0522*
ABD(A-B)	0.0620	1	0.0620	0.7876	0.3957
ABE(A-B)	0.1077	1	0.1077	1.37	0.2693
Residual	0.7869	10	0.0787		
Cor Total	4.74	25			

* Significant, $R^2 = 0.92$, Standard deviation = 0.77, $R^2_{adj} = 0.85$

EY					
Model	4686.84	20	234.34	16.78	0.0027*
Linear Mixture	64.74	1	64.74	4.63	0.0340*
AB	150.80	1	150.80	10.80	0.0218*
AC	446.46	1	446.46	31.96	0.0024*
AD	44.60	1	44.60	3.19	0.1340
AE	882.83	1	882.83	63.20	0.0005*
BC	57.32	1	57.32	4.10	0.0986*
BD	105.74	1	105.74	7.57	0.0402*
BE	77.87	1	77.87	5.57	0.0647*
ABC	189.42	1	189.42	13.56	0.0143*
ABD	47.52	1	47.52	3.40	0.1244
ABE	61.07	1	61.07	4.37	0.0908*
ACD	92.35	1	92.35	6.61	0.0500*
ACE	727.32	1	727.32	52.07	0.0008*
ADE	1.73	1	1.73	0.1239	0.7392
BCD	18.45	1	18.45	1.32	0.3024
BCE	1067.50	1	1067.50	76.42	0.0003*
BDE	116.82	1	116.82	8.36	0.0341*
ABCD	189.10	1	189.10	13.54	0.0143*
ABCE	124.22	1	124.22	8.89	0.0307*
ABDE	94.83	1	94.83	6.79	0.0479*
Residual	69.84	5	13.97		
Cor Total	4756.68	25			

* Significant, $R^2 = 0.96$, Standard deviation = 0.65, $R^2_{adj} = 0.93$

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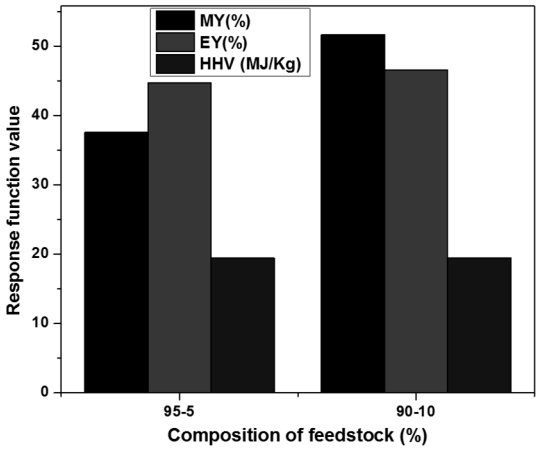


Figure 3. Effect on catalyst on the MY, EY, and HHV of the biochar

INFLUENCES OF PROCESS PARAMETERS ON EY AND HHV OF THE TORREFIED BIOMASS

The MY, EY, and HHV are the major variables used in this research to describe the influence of the process parameters (heating temperature, residence time, and particle size) and the component mixture (sawdust and $CaHPO_4$) on the characterization of the biochar. The feedstock mass fraction involved in the production of biochar after thermal pre-treatment denotes the MY. The MY decreased as the temperatures of torrefaction increased as shown in Figure 4a. The MY with the same proportion of sawdust and $CaHPO_4$ at the same residence time and particle size but with varied heating temperatures for four different cases was deduced from Table 2. Case A illustrated experimental runs 2 and 18 while Case B illustrated runs 11 and 19. Case C and Case D represented experiment runs 12 and 33, and 8 and 30 respectively. The MY for Case A, Case B, and Case C decreased from 67.26% to 37.56%, 42.73% to 36.30%, and 60.86% to 35.17% respectively as the temperature increased from 200 °C to 300 °C. Also, as the heating temperature during torrefaction increased from 255 °C to 300 °C (Case D), the MY of the biochar was reduced from 66.80% to 37.83%. The reduction in the MY of the biochar could probably be due to the evaporation of volatile matter and thermal decomposition of hemicellulose and partial decomposition of lignin and cellulose (27).

APTEFF, 53, 1-302 (2022)
DOI: https://doi.org/10.2298/APT2253109O
BY-NC-ND
UDC: 66.011:635.054:661.635.41
BIBLID: 1450-7188 (2022) 53, 109-122
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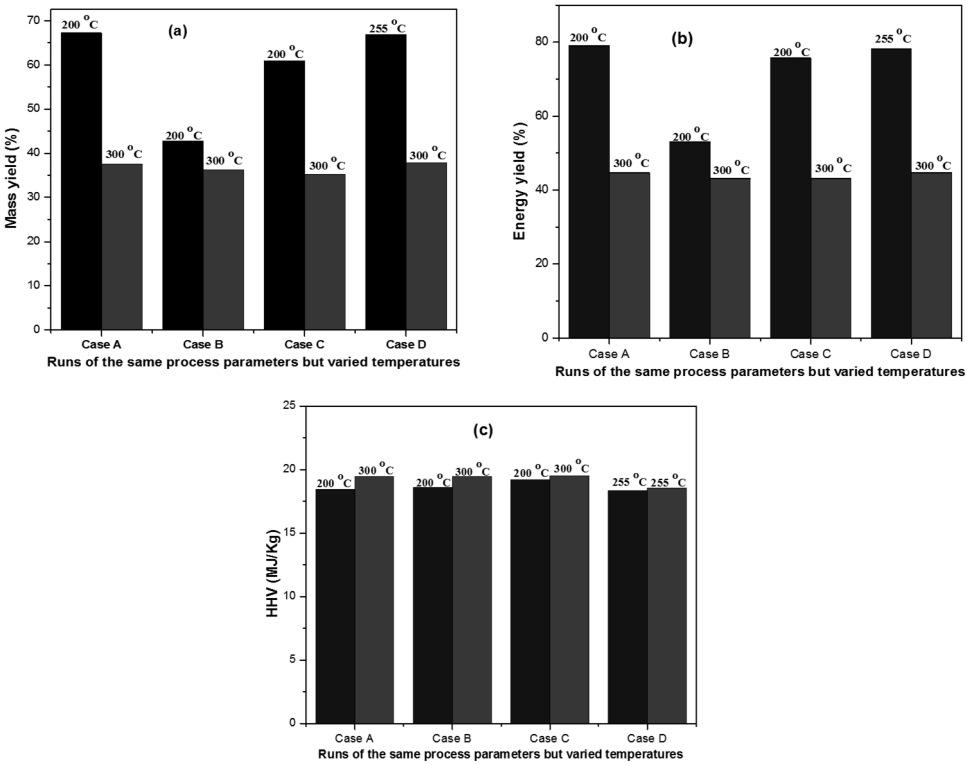


Figure 4. Effects of temperature on the (a) MY (b) EY, and (c) HHV of biochar after torrefaction

EY represents the total quantity of energy in the biomass conserved after torrefaction. It is dependent on the MY and HHV (26). The EY decreased significantly as the heating temperature increased. In Case A, B, and C, EY reduced from 79% to 44.59%, 53% to 43.03%, and 75.71% to 43.06% respectively, as the temperature increased from 200 °C to 300 °C (Figure 4b). likewise, the EY decreased from 78.12% to 44.70% as the temperature increased from 255 °C to 300 °C. These concurred with the findings of Neves et al. (28). However, the HHV increased from 18.43 MJ/Kg to 19.46 MJ/Kg, 18.60 MJ/Kg to 19.46 MJ/Kg, and 19.21 MJ/Kg to 19.52 MJ/kg for cases 1, 2, and 3 respectively as the temperature during torrefaction increased from 200 °C from 300 °C (Figure 4c). The torrefaction of the sawdust at low temperature produced the biochar of low HHV because the disintegration of the cellulose and hemicellulose matter of the biomass was minimal (29). The increase in HHV at a higher temperature may be due to the components of lean energy being lost and the preservation of the developed rich energy components (30).

The influences of residence time on the torrefaction of biomass with 90% of sawdust with 10% catalyst at a constant temperature of 300 °C and particle sizes of 3 mm were investigated. The analysis revealed (Figure 5a) that the rise in residence time (from 15 min to 30 min) resulted in a decrease in MY and EY from 37.22% to 35.17%, and 44.72% to

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43.06% respectively. However, the HHV of the biochar gradually increased from 18.85 MJ/kg to 19.52 MJ/Kg respectively. At higher residence time, it was observed that the effects on the biochar were insignificant when compared to the effects of high temperature because of the rapid degradation of hemicellulose under severe torrefaction conditions (31). Singh et al. (26) affirmed that the oxygenated group that was produced during torrefaction led to reduced MY and higher HHV during longer residence time.

The effect of particle size on the torrefied biomass (92% of sawdust and 8% of $CaHPO_4$) at a constant temperature of 200 °C and residence time of 15 min was investigated. Increasing the particle size from 1 mm to 3mm led to an increase in the MY, EY, and HHV as shown in Figure 5b. The MY, EY, and HHV slightly increased from 42.73% to 48.61%, 53% to 60.42%, and 18.50 MJ/Kg to 18.6 MJ/Kg respectively. This finding concurred with the results of Sukiran et al. (31) and Wang et al. (32).

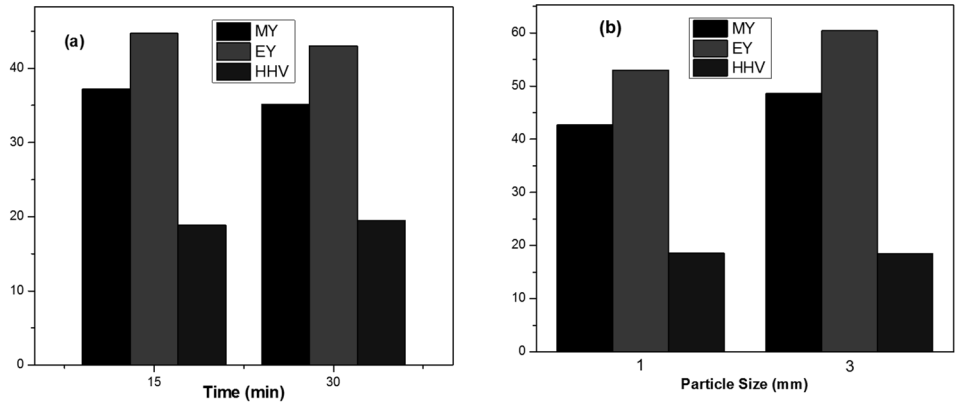


Figure 5. Effect of (a) residence time, and (b) particle size on the torrified biomass

PHYSIO CHEMICAL PROPERTIES OF RAW AND TORREFIED BIOMASS AT OPTIMAL CONDITIONS

The proximate analysis of the raw biomass (sawdust) and biochar at optimal parameters is shown in Table 4. The results revealed that the moisture content, ash content, fixed carbon, and volatile matter for the sawdust is 7.12 wt.%, 2.36 wt.%, 24.88wt%, and 65.64wt% respectively. Biomass is a suitable solid fuel with a higher burning propensity and higher energy density because it has high fixed carbon and low content of ash and moisture (31). The elemental composition of the biomass and the biochar at optimal torrefaction conditions are presented in Table 5. In biomass, carbon (45.46 wt.%) and hydrogen (3.58 wt.%) are the major sources of energy during combustion. The oxygen content (49.79 wt.%) in the biomass is high and reduces its heating value (15.69 MJ/Kg) because oxygen supports the complete combustion of the biomass which serves as fuel (26). In the case of the elemental compositions of the biochar at the optimum torrefaction condition, the carbon content increased to 66.52 wt.% whereas the oxygen content was reduced to 27.42 wt.%. The HHV of the biochar at optimum torrefaction conditions was improved to 19.59 MJ/Kg due to the decrement of the oxygen content after torrefaction. The contents of nitrogen and sulphur are

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minimal for biomass and biochar, thereby releasing a smaller amount of NOx and SOx into the environment (33).

Table 3. Proximate analysis of raw and torrefied biomass at optimal conditions

Components	Raw biomass	Torrefied biomass
Moisture content (wt.%)	7.12	5.62
Ash content (wt.%)	2.36	1.41
Fixed carbon (wt.%)	24.88	42.45
Volatile matter (wt.%)	65.64	49.52
HHV (MJ/Kg)	15.69	19.59

Table 4. Ultimate analysis of the biomass and biochar at optimal torrefaction conditions

Elemental compositions	Biomass	Biochar
Carbon (wt.%)	45.46	66.52
Hydrogen (wt.%)	3.58	3.61
Nitrogen (wt.%)	1.02	2.07
Sulphur (wt.%)	0.15	0.38
Oxygen (wt.%)	49.79	27.42

CONCLUSION

This study deals with the optimization of HHV and energy yield from torrefaction of the mixture of sawdust and calcium hydrogen phosphate in a tubular furnace at varied temperatures, residence time, and particle size. Results indicated that reaction temperature and time were more effective for HHV and EY than the particle size. The maximum HHV of 19.59 MJ/Kg and EY (76.37%) was obtained at an operating condition of 245 °C temperature, 22 min time, and 3 mm particle size. The interactions between the process variables were accurately modelled. The mathematical models for the HHV and EY for the torrefaction using the OCD indicated a good fit with R^2 of 0.92 and 0.96, respectively. The addition of catalyst ($CaHPO_4$) at 10% reduced the ash content but enhanced the fixed carbon content of the biochar. Torrefaction of the sawdust-catalyst mixture would be an efficient method for improving the properties of *Albizia zygia* wood. Further study can be carried out to combust the solid fuel in a grate furnace for a steam power plant.

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