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Effects of Varying Binder Proportions to the Mechanical, Physico-Chemical and Combustion Properties of Banana (*Musa acuminata x balbisiana*) Leaves-Derived Biochar Briquettes

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ABSTRACT

The study aimed to characterize the mechanical, physico-chemical and combustion properties of biochar-derived briquettes from the banana (Musa acuminata x balbisiana) leaves and determine the optimum binder proportion of the briquettes. Physical properties include moisture content, density, and compressive strength. Physico-chemical properties were evaluated using proximate analysis which includes volatile matter, ash, and fixed carbon. Combustion properties were comprised of ignition time and burning rate.

Freshly harvested, oven dried, and milled banana leaves underwent slow pyrolysis at 300 °C for 8 hours. The retrieved biochar was combined with varied concentrations of cassava starch binder at 10%, 30%, and 50%. It was then molded into briquettes and dried at 80 °C until 5% moisture content was achieved.

Results showed that as binder proportion increased, compressive strength, volatile matter, and ignition time also increased. However, an increase in binder proportion induced a decrease in burning rate. Moreover, compressive strength, volatile matter, ignition time, and burning rate are found to be statistically significant in relation to binder proportion as analyzed using One-way ANOVA at 95% confidence level. Other parameters that were statistically insignificant in relation to binder proportion included moisture content, density, ash content, and fixed carbon. After performing optimization through Simplex Lattice in Design Expert, optimum cassava binder proportion was found to be 41.14%.

Keywords: *banana leaves, Musa acuminata x balbisiana, slow pyrolysis, biochar briquette, proximate analysis, binder proportion*

INTRODUCTION

Pyrolysis is the process of breaking down of large molecules of hydrocarbons into simpler compounds in the form of char, liquid, and gas undergoing in a temperature range of 300-650 °C which influences the amount and construction of the resulting materials (Basu, 2010). One of the raw materials for thermochemical conversion of biomass to biofuel is agricultural wastes. It has high organic matter content in which biofuel is mainly derived from. Abdollahi-Neisiani et al. (2013) reported that when biomass is used to form biofuel, the CO_2 emission does not contribute to greenhouse gases since biomass is considered carbon neutral. The biomass recycles all its acquired carbon content back to the atmosphere where the carbon is initially acquired from during the phase of biomass as a plant. Moreover, to generate a sustainable energy resource without compromising food consumption, underutilized agricultural wastes, such as banana leaves, are being used.

Banana is one of the major crops cultivated in the Philippines. It is considered as a perennial crop that reaps only once per plant while the pseudostem and leaves are cut down after harvesting the fruits to give way for new suckers to grow (Padam et al., 2014). There was a 9.01 million metric ton (MT) of banana produced in 2022 as the number of bearing hills grew for cultivation (Philippine Statistics Authority, 2023). This further supports that large volume of harvest prevails large volume of agricultural wastes. According to Fernandes et al. (2012), after harvesting 1000 kg banana fruit, fruit wastes comprised 10% of the overall weight while 4000 kg of lignocellulosic wastes are produced coming from 73% pseudostem, 3.92% stalks, 11.76% leaves, and 10.78% peels.

Banana wastes, especially banana leaves, prove to be a good candidate as a renewable energy source in the form of briquettes. According to the study conducted by Kabenge, et al. (2018), direct relationship of lignin content and high calorific value existed in banana agricultural wastes such leaves, pseudostem and peels, in which banana leaves attained the highest high heating value of 17.57 MJ/kg at 10.58% of lignin. In a study conducted by Fernandes et al. (2012), pyrolyzed banana leaves and pseudostem compete with the usual biomass which yielded 14.7%, and 17.5% fixed carbon, respectively.

Briquettes assume the shape of their molders and resist separation of crushed biochar due to the adhesive capability of its binders. The combination of water and starch, heated at certain temperature, is usually used as binder. Mills (1908) stated that starch is used as binders for soft coals due to its firm binding properties yielding superior qualities than any binders because it resists volatilization prior to ignition and contributes no exhaust in the atmosphere during combustion. Young (2015) supported that this process further established open linkages for hydrogen to attract water molecules through breaking down of intermolecular bonds which, when used as a binder, can withstand high pressure coal briquettes at a concentration of 4% starch.

Briquettes assume shape such as cylinder or hollow tube. Abdullahi et al. (2017) used a cylindrical briquette having a diameter of 19.4 mm and height of 50.2 mm molded at 150 kg/cm^2 for 2 minutes. The different sizes of making briquettes may also depend on the equipment to be used to produce it.

Generally, the study aimed to establish the mechanical, physico-chemical, and combustion properties of banana leaves-derived biochar briquettes. Specifically, the study aimed to:

1. Analyze the relation of binder proportion to the compressive strength, proximate analysis, ignition time, and burning rate of biochar briquettes;
2. Evaluate the yield (mass basis) of fresh banana leaves to produce biochar; and
3. Determine the optimum cassava starch binder proportion for biochar-derived Briquettes.

METHODOLOGY

Biochar Production

Preparation of Samples

After harvesting the banana fruits, mature banana (*Musa acuminata x balbisiana*) leaves (during harvest time) were obtained from a banana farm in San Juan, Sta. Cruz, Laguna. The mid rib section of the leaves was cut off and was not included in the succeeding processes. Samples were then transported to the Grain Laboratory of the Agricultural, Food and Bio-Process Engineering Division (AFBED), Institute of Agricultural and Biosystems Engineering (IABE), College of Engineering and Agro-Industrial Technology (CEAT), University of the Philippines Los Baños, College, Los Baños, Laguna.

Initial Moisture Content Determination and Drying

To determine the initial moisture of the banana leaves, samples were subjected to be oven-dried at 105 °C for 72 hours. Simultaneously, a bulk sample of banana leaves were dried using an oven (Memmert Universal Oven UF260) at varied increasing set of temperatures from 45 °C, 50 °C, 70 °C and 90 °C for a period of seven (7) days until 10% moisture content by weight was achieved. This set of samples were used for further processing. The Memmert Universal Oven UF260 has a working temperature range of at least 5 °C above ambient temperature up to 300 °C and has an internal volume of 256 L that can accommodate the drying process of huge amount of samples.

Particle Size Reduction

The particle size of dried leaves was reduced using a hammer mill developed by the UPLB's Center for Agri-Fisheries and Biosystems Mechanization (BIOMECH). The rotating hammers (blades) cut into the samples for size reduction. The milled dried leaves were subjected to a Ro-Tap sieve shaker using a sieve with Mesh no. 10 to attain particle size of less than 2 mm (Bawar, 2019). At fine sizes, voids, or air spaces inside the pyrolyzer tank can be minimized.

Pyrolysis

The pyrolyzer used is composed of a reactor where the samples are to be placed, a burner that has a manually controlled knobs to vary the heat applied, and a heat source from a liquefied petroleum gas (LPG). The milled dried leaves were placed inside the pyrolyzer's reactor with samples occupying at least 80% of the reactor's total volume. As heat is supplied from a LPG, the volatile molecules start to form, and thus occupying the reactor until volatiles are forced out of the reactor (Brewer & Brown, 2012). The dried banana leaves were subjected in the reactor at 300 °C for 8 hours. A thermocouple type K coupled to a temperature data logger (Lutron BTM-4208SD) was used to monitor the temperature inside the tank. The biochar was left in the reactor to cool off before it was collected. The biochar collected was not uniformly formed into char, a partially burned by-product of pyrolysis having a blackened physical characteristic. Only the char at the bottom of the reactor was used to form into briquettes.

Application of Binders and Molding into Briquettes

The binder was added to hold the particles of biochar together and mold to the form of a briquette. The binder used was cassava starch processed to form a paste. Ezéchiel et. al (2022) claimed that cassava starch increases the durability, and density, and has the most improved lower heating value (LHV) at 19.082 ± 0.381 MJ/ kg. To produce the paste, 150 g cassava starch was mixed with 200 ml ambient water temperature and 800 ml boiling water. Then, the paste was mixed with biochar at varying proportions of 10%, 30%, and 50% by mass basis. After combining the biochar and the binder, the mixture was placed in a diamond-shaped briquette molder. It was operated through manual compression.

Drying of Briquettes

Biochar derived briquettes (**Figure 1**) underwent oven drying to approximately attain 7% moisture

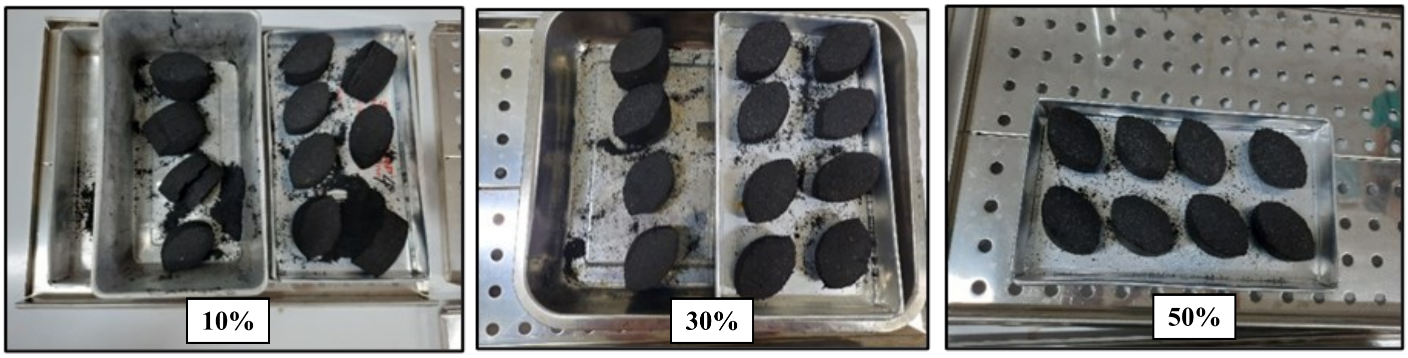

Figure 1. Biochar briquettes at different binder proportion.

content. To do this, briquettes were oven dried at 80 °C until no significant change in weight was observed. A Carbolite oven was used to dry the briquettes.

The process flow of the biochar briquette production is shown in **Figure 2.** Residuals that were not part of the succeeding steps include the mid-rib section of banana leaves, dried and hammer milled leaves with greater than 2 mm particle size, and other pyrolysis by-products such as bio-oil and uncondensable gases.

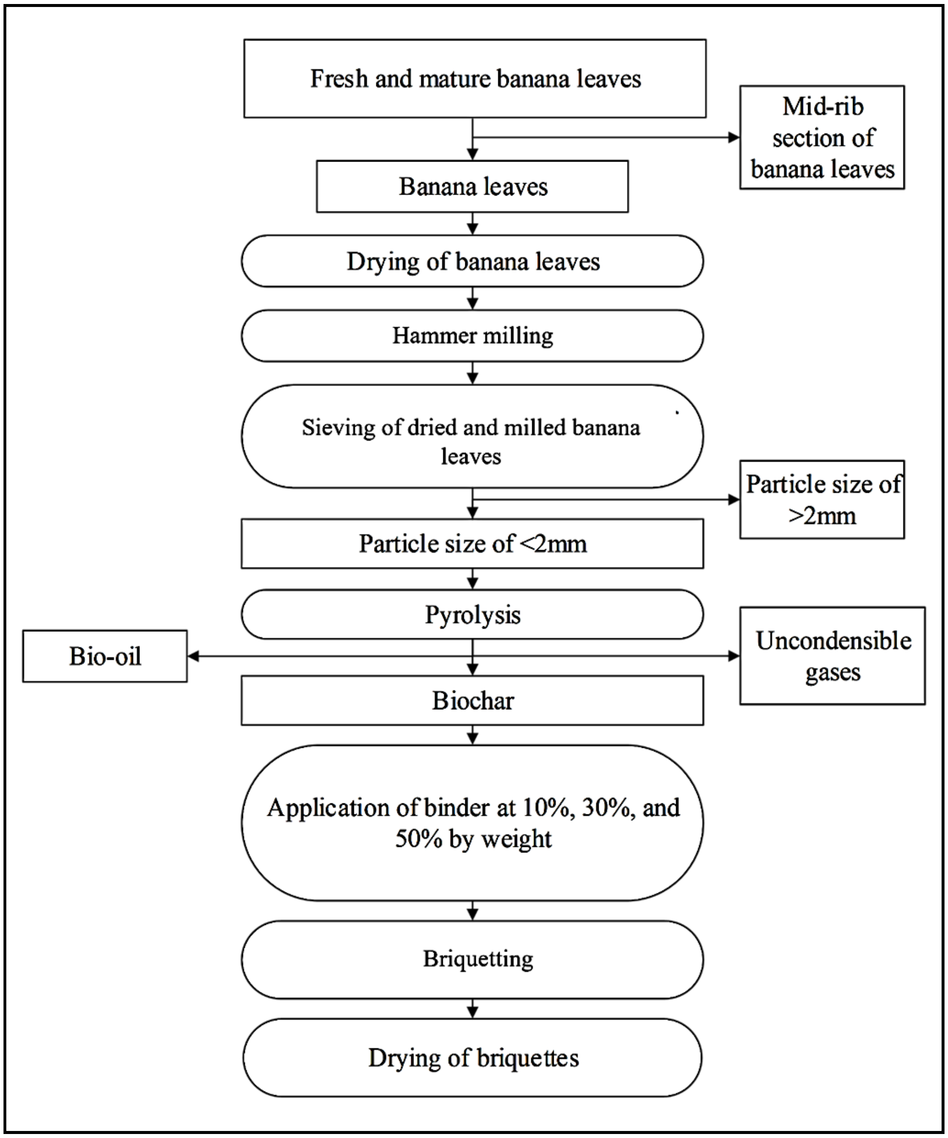

Figure 2. Process flow of biochar briquettes production.

Moisture Content Determination

The moisture content of briquettes was measured using a moisture analyzer (Moisture Analyzer Digital XY-100MW). About 2 g of samples were placed inside the plate. The moisture was recorded until it stabilized.

Density Determination

The density was measured by determining the ratio of the mass of the briquette to its volume. The mass was measured using an analytical balance. On the other hand, the volume was computed as shown in **Equation 1**. The shape of the briquettes was assumed to be a prolate sphere. Images of the briquettes were captured, and its dimensions were scaled and measured using AutoCAD 2018.

$$Volume = \frac{4}{3}\left(\pi a b^2\right) \qquad \textbf{\textit{Equation 1}}$$

where:

a is the major semi-axis of the ellipse of rotation or radius on the major axis (cm);

b is the minor semi-axis of the ellipse of rotation or radius on the minor axis (cm)

Compressive Strength Determination

The dried briquettes were the subjected in a Universal Testing Machine (UTM) (Instron 4411) for compressive test with crosshead speed set at 10.00000 mm/min. The weakest side was first determined by observing and subjecting the briquettes in two (2) positions. The first one was positioned with the oval or diamond shape facing the thick metal plate. The other one was positioned with the side of the diamond shape facing the thick metal plate which, then, was found to be the weakest side of the briquette.

Proximate Analysis

Using two (2) furnaces, the proximate analysis was determined yielding the percentage of volatile matter, ash, and fixed carbon. The samples were subjected at different temperatures to perform separately the methods for volatile matter and ash content determination. The American Standard Testing Material (ASTM) was used as the basis of analysis. A certain amount of briquette samples was placed inside a covered crucible.

Percentage Volatile Matter

According to Doshi et al. (2014), ASTM D 3175-07 (2009) was used to determine the volatile matter. One gram of briquette was placed inside a covered crucible and heated in a muffle furnace (Barnstead|Thermolyne Type 1300 Furnace) at 950 $\pm$ 10 °C for 7 minutes. Bawar (2019) reported that after heating, the crucibles need to be placed in a desiccator. This is to dissipate the heat without changing the moisture content.

Percentage Ash Content

As reported by Doshi et al. (2014), ash content determination was also done using ASTM D 3174-04 (2009). The samples used after volatile matter determination were subjected inside a muffle furnace (Yamato FO510) having a temperature of 600 $\pm$ 10 °C for 4 hours. After the burning process, the crucibles and covers were placed in a desiccator to cool down the temperature and prevent any moisture absorption before weighing the samples in an analytical balance.

Percentage Fixed Carbon

The amount of fixed carbon was determined by subtracting the sum of percentages of ash content, and volatile matter from 100%.

Ignition Time Determination

The ignition time was determined using a kerosene lamp where a timer measured the time starting from ignition until a stable burn phase was achieved (Jentilizo, 2019). Ignition time was also termed by Oladeji (2010) as the afterglow upon which time was recorded until a stable flame or noticeable glow was achieved for an oven dried briquette under a Bunsen burner.

Burning Rate Determination

After measuring the ignition time, the briquette sample continued to ignite in which for every 2-minute interval, the weight of the wire and the briquette was measured until no significant change in weight was observed (Jentilizo, 2019). The briquettes retained their shape until the outer layer fell out as ashes. The burning rate computation was lifted from Onuegbu et al. (2011) and presented in the Equation 2:

$$BR = \frac{w_i - w_f}{t} \qquad \textit{Equation 2}$$

where:

W_i is the initial weight of the sample (g)
W_f is the final weight of the sample (g)
t is the time consumed (min)

Statistical Analysis

The parameters of biochar briquette that were subjected to statistical analysis include moisture content, density, compressive strength, volatile matter, ash, fixed carbon, ignition time, and burning rate. One-way Analysis of Variance (One-way ANOVA) was the statistical tool used to determine whether the parameters yield statistical significance at 95% significance level. For the optimization, Simplex Lattice mixture design for two-level and two (2) components in linear order was used in the Design-Expert software. The goodness of fit statistical model was used to determine how well the predicted values differs from the observed values.

RESULTS AND DISCUSSIONS

Mass Balance

The mass balance for biochar production is shown in **Figure 3**. Upon the collection of banana leaves, the midrib section was left unmeasured in the field. Thus, mass balance started with only the leaf part. The midrib section of a leaf comprised of 54.45% of the total weight of the whole leaf (Ennos et al., 2000). The initial moisture content of fresh banana leaves is approximately 70.64 %. Upon subjecting the dried and milled banana leaves to pyrolysis at 300 °C for 8 hours, only 2.56 % formed into biochar.

Mechanical Properties

The examined mechanical properties of the biochar briquettes include moisture content, density, and compressive strength. These were observed in relation to different binder proportions as shown in **Figure 4**. Each parameter was subjected to One-way ANOVA at 95% significance level.

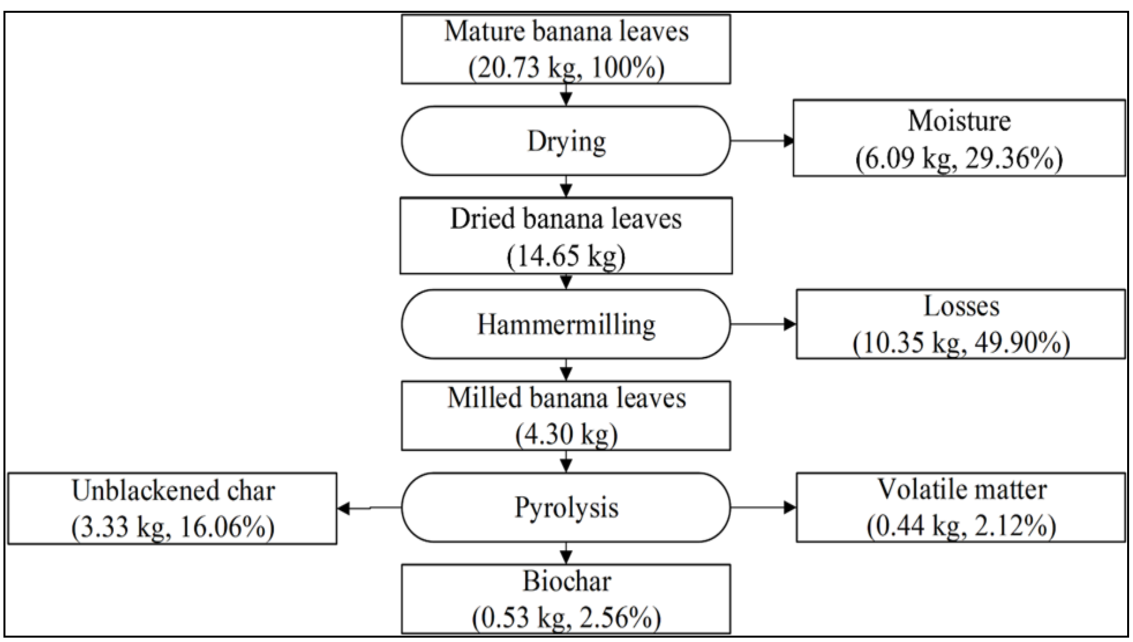

Figure 3. Mass balance of banana leaves as it undergoes biochar production.

Moisture Content

According to Oyelaran et al. (2018), the acceptable range of briquettes' moisture content is 5-10 % from which other physical properties are not significantly affected. In **Figure 4**, a range of 7.09 – 7.88% moisture content for all the binder proportions were observed for the biochar briquettes. Using One-way ANOVA, moisture content is statistically insignificant in relation to binder proportion.

Density

Obermberger and Thek (2004) claimed that particle density affects the bulk density as well as combustion properties in which briquettes with high density have prolonged burn-out time than briquettes with low density.

Figure 4 shows the average computed density with a range of 0.32 – 0.42 g/cm^3 for all the binder proportions. Meanwhile, a close comparison with the study conducted by Bawar (2019) showed that bulk density of mango seed husk with binder at 0.25 – 0.39 g/cm^3, and relaxed density of mango seed husk briquettes ranged from 0.34 – 0.69 g/cm^3. However, after conducting One-way ANOVA, density of the biochar briquettes was found to be statistically insignificant in relation to binder proportion.

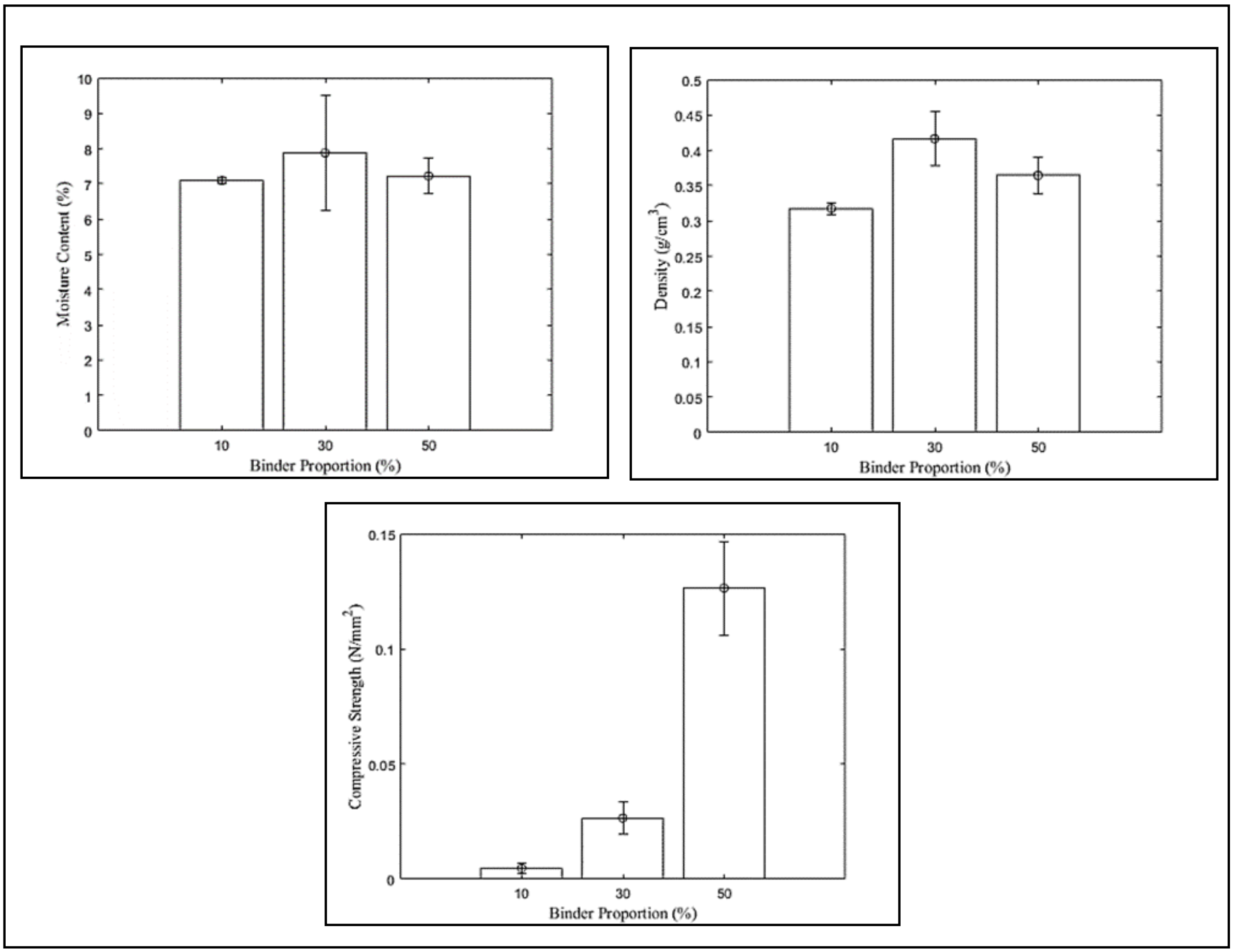

Figure 4. Average moisture content, computed density, and computed compressive strength

Compressive Strength

Jani (2016) said that a strong compressive strength helps to enhance the handling and stacking pattern of briquettes especially when transporting. Kers et al. (2010) also supported that high compressive strength induce high briquette strength through which a reduction in ambient humidity absorption is observed.

Figure 4 also shows that at higher binder proportion, compressive strength is also higher. A range of 0.0047 – 0.0265 N/mm^2 for all the binder proportions were observed. This also showed a statistically significant factor in relation to binder proportion from the analysis made using One-way ANOVA.

Moreover, a similar trend is observed in a study conducted by Sen and Annachhatre (2016) wherein as the binder increases, the compressive strength also increases. The same trend was also observed from the study of Jentilizo (2019) where mango husk briquettes had increased compressive strength from 10% to 30% binder proportion at an average range of 0.99 – 4.38 N/mm^2. Hamid et al. (2016) claimed that due to enhanced adherent capacity of the binder, concentration, bonding, and densification helped to optimize maximum compressive strength.

The only mechanical property of the biochar briquettes in relation to binder proportion that was found to be statistically significant was compressive strength. The moisture content and density showed statistically insignificance in relation to binder proportion.

Proximate Analysis

The proximate analysis for physico-chemical properties of biochar derived briquettes were done for volatile matter, ash content, and fixed carbon. One-way ANOVA at 95% significance level was performed to determine if each parameter was statistically significant with binder proportion.

Volatile Matter

According to Fernandes et al. (2012), the high volatile matter indicates that banana leaves have rich organic content, and high vulnerability to thermal degradation. Volatile matter affects the amount of smoke and quality of flame a briquette may produce where lesser volatility makes ignition difficult, creates few smokes and flame (Oyelaran et al., 2018).

Figure 5 showed that as the binder proportion increase, volatile matter also increases ranging a range of 36.5 – 41.3 % volatile matter for all the binder proportions. Additionally, One-way ANOVA yielded that volatile matter was statistically significant in relation to binder proportion.

A great difference in volatile matter was observed in other studies especially those that did not undergo slow pyrolysis. Yang et al. (2005) reported an acceptable range of 65-85% of volatile matter for biomass fuels. In a study done by Fernandes et al. (2012), pyrolyzed banana leaves obtained 77.8% volatile matter. Additionally, Bawar (2019) reported volatile matter from mango seed husk briquettes at 80-84 %. However, the resulting data were supported by the analysis using One-way ANOVA in which the volatile matter yielded a direct relationship with the binder. Moreover, the deviation of volatile matter can also be attributed to slow pyrolysis. This further leads to an additional exposure of samples to gaseous degradation process and decreased the organic matter and vulnerability to thermal degradation of banana leaves as it formed into biochar briquettes.

Ash Content

After combustion, ash is an inorganic and incombustible residue material which lessens handling and burning capacity, as well as combustion efficiency (Oyelaran et al., 2018). Oladeji (2010) said that low ash content is one of the ideal qualities of briquettes from agricultural wastes upon which less ash content correlates to good fuel source. Thus, ash is desired to be as minimum as possible.

A range of 37.0 – 39.8 % ash for all the binder proportions were observed as shown in **Figure 5**. Unlike volatile matter, binder proportion has a

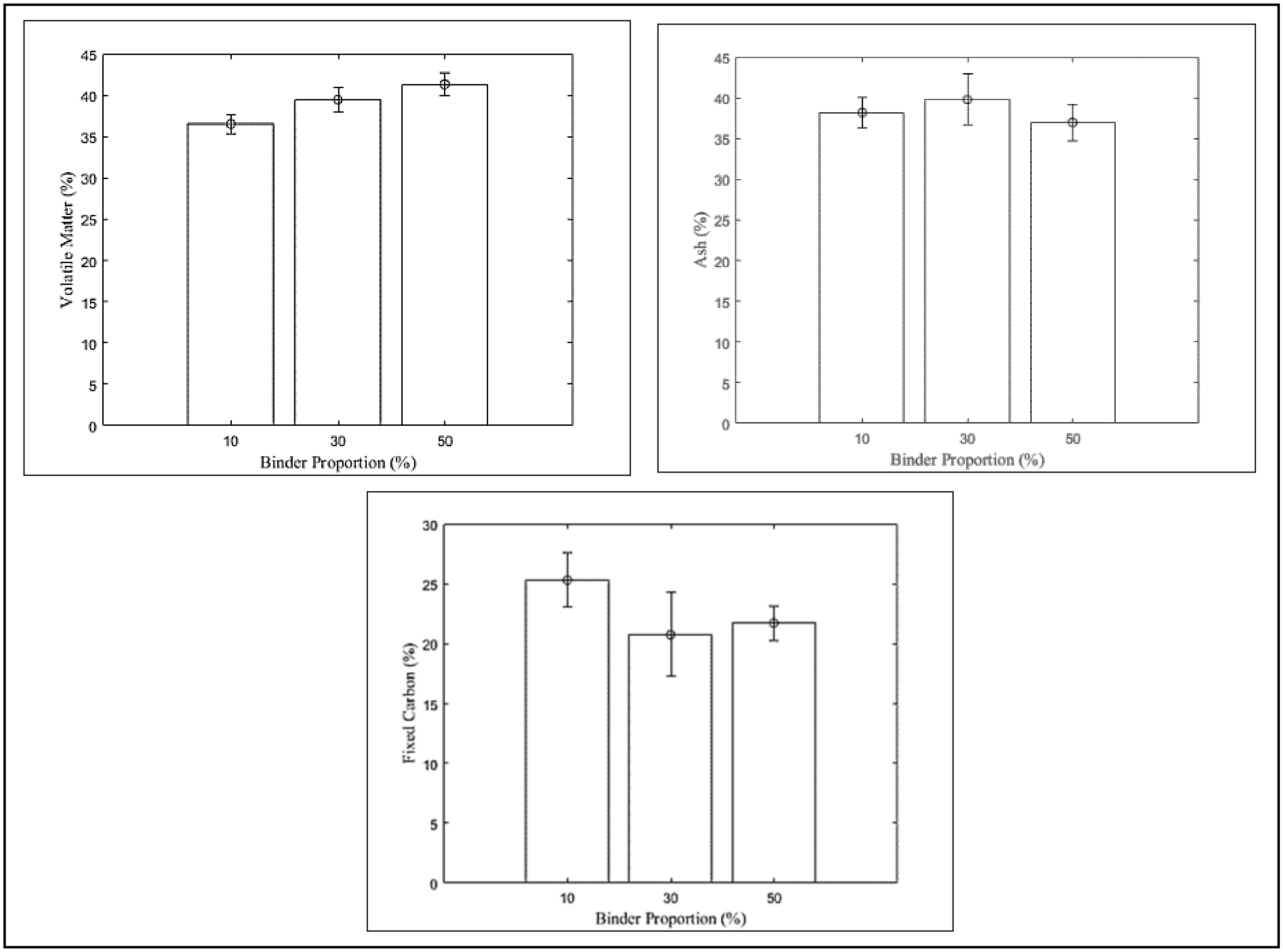

Figure 5. Average volatile matter, ash content, and fixed carbon of biochar briquettes in relation to binder proportion.

statistically insignificant influence on ash content.

Fernandes et al. (2012) reported 7.44% ash content in pyrolyzed banana leaves. Ash content of 9.28 – 14.30 % was reported by Bawar (2019) for the mango seed husk briquette. Also, Yang et al. (2017) claimed that ash content of certain biomass increases based on the process the biomass undergone from raw biomass to biochar at 300 °C, and then biochar at 500 °C. It is also observed that raw materials with higher ash than other raw materials also yielded a higher ash in its biochar form. Moreover, Lewandowski and Kicherer (1997), as cited by Yang et al. (2017), reported that differences in ash of biomass are due to ash resulting chemical compounds such as calcium carbonate, potassium silicates, iron, and other metals. Thus, the reported high ash in this study for banana leaves can be accredited to the process of pyrolysis, as well as the chemical composition of banana leaves.

Fixed Carbon

The computed fixed carbon for this study came from the difference of the added values of volatile matter and ash to 100%. The moisture content is omitted to determine fixed carbon as adopted from study done by Bawar (2019). The moisture content is assumed to have negligible amount since the briquettes were dried to as low as possible prior to proximate analysis.

A range of 20.7 – 25.3 % fixed carbon for all the binder proportions were observed in the biochar briquettes as presented in **Figure 5**. A statistically insignificant relationship between fixed carbon and binder proportion was generated using One-way ANOVA.

Studies involving banana leaves and briquetting showed lesser fixed carbon than the reported values in this study. Abdullah et al. (2014) characterized banana leaves to have 15.6% fixed carbon. Moreover, Fernandes et al. (2012) declared that slow pyrolyzed banana leaves have 14.7 % fixed carbon. Similar studies on briquetting include Sellin et al. (2013) who reported 15.60 % fixed carbon for briquetting dried banana leaves. Bawar (2019) generated 5.69 – 8.31 % fixed carbon for mango seed husk briquettes. Doumer et al. (2015) asserted that increased high heating values is affected by fixed carbon, thus offers a characteristic to be considered as good for fuel source.

In summary, volatile matter has the sole statistical significance to binder proportion in all the parameters in proximate analysis.

Combustion Properties

Ignition Time

Rajkumar and Venkatachalam (2013) said that combustion properties, as well as transport and storage, of briquettes is improved with increased density. Demirbas (2004) reported that compressed biomass briquettes took longer to ignite due to lesser void fractions and increased density. Arellano et al. (2015) also claimed that ignition properties are intensified when volatile matter and moisture content were increased.

Ignition time for binder proportions is shown in **Figure 6**. An average range of 24.4 – 40.0 min for all the binder proportions was observed. One-way ANOVA gave a statistically significant result in the relationship of ignition time and binder proportion.

The reported ignition time in this study is higher than the study done by Oyelaran et al. (2018) where banana leaves briquette had ignition time of 64.08 to 180.96 seconds. Additionally, Jentilizo (2019) reported ignition time at 12.00 – 280.24 s for the mango husk briquettes. Moreover, opposite trend was also observed from both studies.

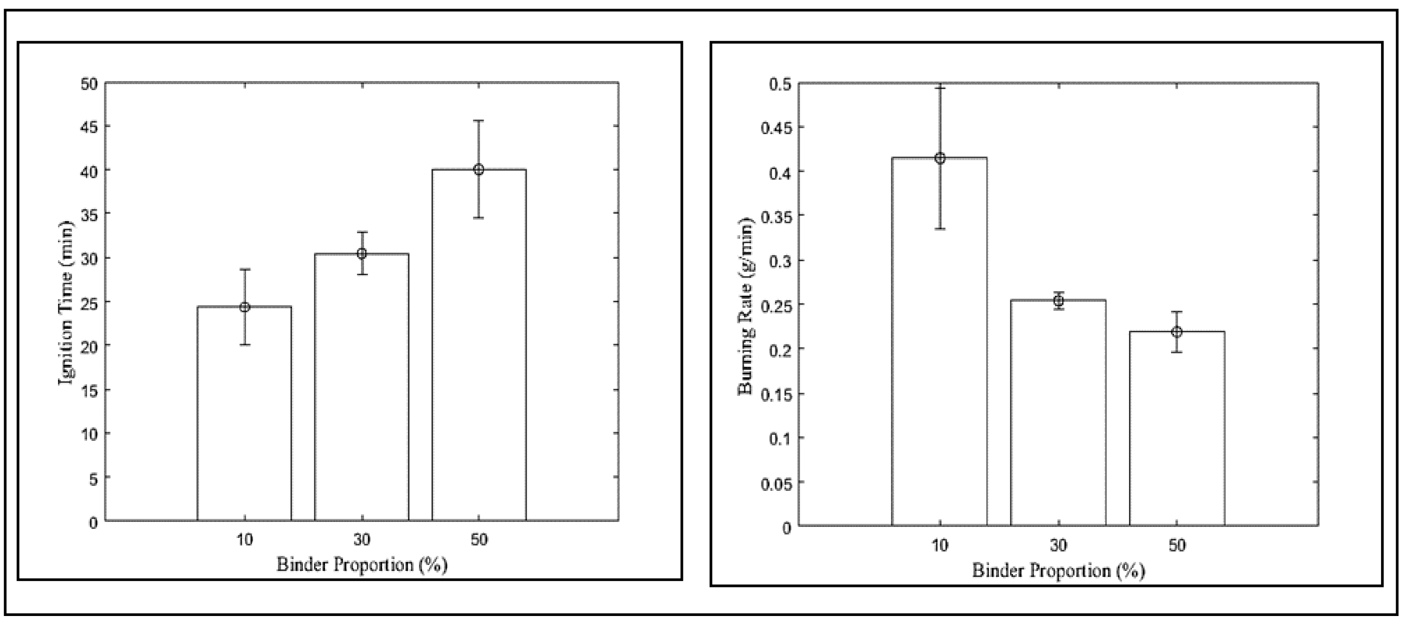

Figure 6. Average ignition time and burning rate of biochar briquettes in relation to binder proportion.

Burning Rate

Burning rate is associated with the capacity of the briquettes to consume the fuel time. Oyelaran et al. (2018) also termed burning rate as combustion rate. The average burning rate for binder proportions is shown in **Figure 6**. An average range of 0.22 – 0.41 g/min for all the binder proportions were observed. Like ignition time, burning rate influenced a statistically significance with respect to binder proportion.

The reported burning rates were higher than the study conducted by Jentilizo (2019) using husk briquettes at 0.19 – 0.26 g/min. The burning rate increased as the biomass content proportion increased. Oyelaran et al. (2018) further implied that higher burning rates indicated that a greater number of briquettes were needed to use than those briquettes with lower burning rates.

Binder Proportion Optimization

ANOVA Tables for Statistically Significant Parameters

As shown in **Table 1**, the parameters that yielded statistically significant p-values for one-way ANOVA were compressive strength, volatile matter, ignition time, and burning rate.

Table 1. Statistical analysis of briquettes' compressive strength, percent volatile matter, ignition time, and burning rate.

SOURCE	RESPONSE MEANS			
	COMPRESSIVE STRENGTH	PERCENT VOLATILE MATTER	IGNITION TIME	BURNING RATE
Sum of	0.0337	46.08	368.69	0.0572
df	2	1	1	1
Mean Square	0.0169	46.08	368.69	0.0572
F-value	109.02	26.75	22.03	18.35
p-value (< 0.05)	< 0.0001	0.0004	0.0022	0.0036

95% degree of confidence ($p < 0.05$)

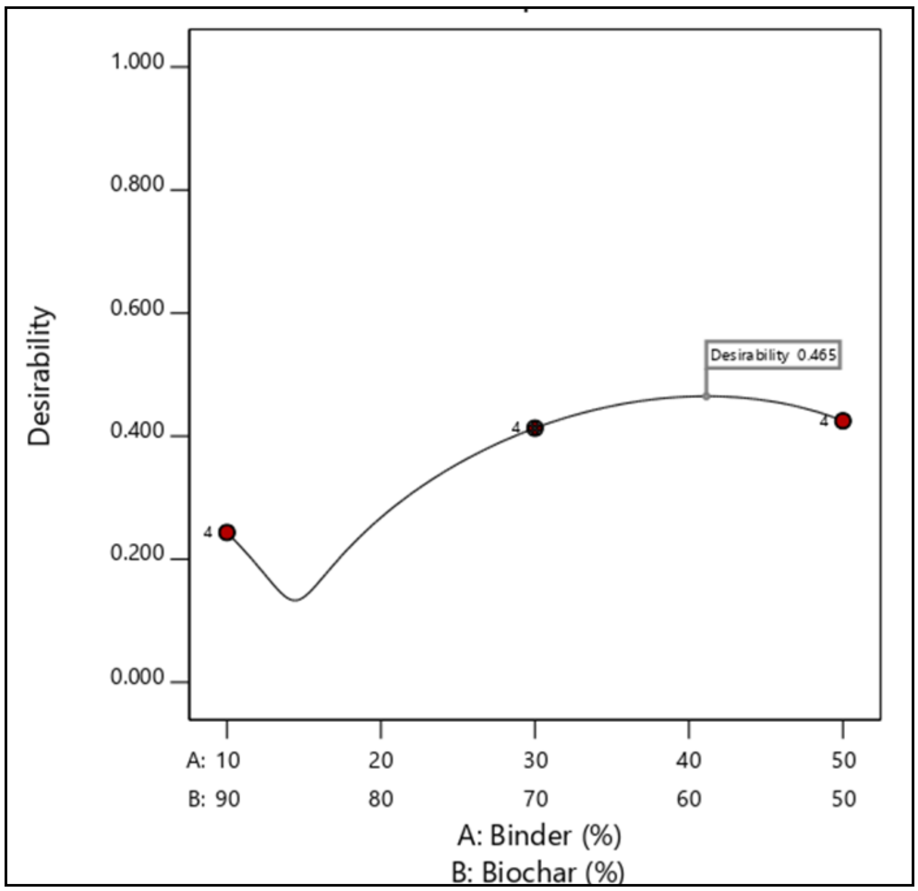

Figure 7. Optimization numerical graph for desirability of optimum binder proportion.

Simplex Lattice Optimization

These parameters were further analyzed using Simplex Lattice mixture design for two-level and two (2) components in linear order for a single block in Design-Expert software to determine optimized desirability. The Simplex Lattice design includes two (2) simplex points, in three (3) augment design with seven (7) runs to replicate and 12 total runs. **Figure 7** exhibits the generated graph showing that the optimal cassava binder proportion is 41.14% with a desirability of 0.465. Alongside the optimum binder are the predicted values of dependent factors such as compressive strength at 0.073 N/mm, volatile matter at 40.0445 %, ignition time at 35.971 min, and burning rate at 0.241 g/min.

Table 2. Fit statistics of compressive strength, volatile matter, ignition time, and burning rate.

PARAMETER	COMPRESSIVE STRENGTH	PERCENT VOLATILE MATTER	IGNITION TIME	BURNING RATE
Standard deviation	0.0124	1.31	4.09	0.0558
Mean	0.0526	39.11	31.61	0.2957
C.V. %	23.67	3.36	12.94	18.89
R^2	0.9604	0.7279	0.7589	0.7239
Adjusted R^2	0.9516	0.7007	0.7244	0.6844
Predicted R^2	0.9295	0.6146	0.5591	0.5159
Adequate Precision	19.5821	8.9588	8.1294	7.4199

Table 3. Linear regression analysis of compressive strength, volatile matter, ignition time, and burning rate.

PARAMETER	COMPRESSIVE STRENGTH	PERCENT VOLATILE MATTER	IGNITION TIME	BURNING RATE
R^2	0.8793	0.9828	0.9837	0.8782

Post Analysis Optimization

Moreover, goodness of fit was used to determine the difference between the observed and expected values of the optimized parameters. **Table 2** showed the fit statistics of the optimized parameters. A difference of less than 0.2 between the Predicted R^2 and Adjusted R^2 is said to be a reasonable agreement. This was observed in all the aforementioned parameters. Additionally, a greater than 4 adequate signal as a result of the ratio between signal to noise, represented as Adequate Precision in the **Table 2**, is desirable to be navigate the design space and is complied by the aforementioned parameters. Additionally, a greater than 4 adequate signal as a result of the ratio between signal to noise, represented as Adequate Precision in **Table 2**, is desirable to be navigate the design space and is complied by the aforementioned parameters.

Furthermore, the average values of the significant parameters that yielded statistically significant results are subjected in a simple linear regression to determine how well the actual data be used to predict an unknown dependent variable from a known independent variable. The coefficient of determination (R^2) of each parameter is summarized in **Table 3**.

SUMMARY AND CONCLUSION

Banana leaves were subjected to pyrolysis to generate biochar as an alternative source of biofuel. Biochar yield is at 11 % by weight from pyrolysis of dried banana leaves at less than 2 mm particle size with 300 °C temperature and 8 hours residence time. The biochar was mixed with different cassava binder proportion of 10%, 30%, and 50% to produce biochar briquettes, which then subjected to different analyses to determine its properties.

Mechanical properties include density, moisture content, and compressive strength. Compressive strength yielded significant effect while density and moisture of the briquettes are not significant in relation to binder proportion. It was also showed that as the higher the percentage of binder proportion, the higher the compressive strength.

The physico-chemical properties of biochar derived were determined using proximate analysis which measured volatile matter, ash content, and fixed carbon. Volatile matter had the only significant effect on binder proportion while ash content and fixed carbon have no significant effect. Likewise, higher binder proportion showed higher volatile matter.

Combustion properties such as ignition time and burning rate were also determined to measure the thermal effectivity of the briquettes. Both ignition time and burning rate yielded significant effect on binder proportion. At higher binder proportion, ignition time is also longer. However, burning rate showed the opposite trend where the lower the binder proportion, the higher the burning rate.

Lastly, optimization through Simplex Lattice showed that cassava binder proportion is optimum at 41.14% with a desirability of 0.465. The predicted values for the dependent factors include compressive strength of 0.073 N/mm, volatile matter of 40.0445 %, ignition time of 35.971 min, and burning rate of 0.241 g/min.

RECOMMENDATIONS

To further improve the study, the following are recommended:

1. Use of smaller size of reactor which is more appropriate for small particle size samples to generate improved biochar yield;

2. Use of briquetting machine that can produce more uniform pressure when applied to mold the briquettes;

3. Compare the shape of briquettes in relation to mechanical properties such as compressive strength, falling strength, and shear strength.

4. Analyze the calorific value and ultimate analysis of biochar briquettes;

5. Determine the cost-benefit analysis of using banana leaves-derived biochar briquette as an alternative fuel source;

6. Perform and examine an optimization study with independent variable such particle size, moisture content, and shape of briquettes; and

7. Futher explore other potential parts of saba banana as alternative biofuel.

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