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Original Article

Evaluation of briquettes produced from extractive-free residues of hardwood species using Gum-Arabic as binder

OPEN ACCESS

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ABSTRACT

This study was undertaken to determine some physico-mechanical and combustion properties of briquettes produced from extractive-free wood of *Sterculia tragacantha, Anthocleista vogelii,* and *Trichilia spp.* The extractive was removed from the residue using hot-water method. Gum-arabic was used as binding agent, it was mixed in 100ml of water to form gelatin. Sawdust of 50g was blended with gum-arabic binder (5, 10 and 15g for gum arabic) and was hand-fed into the briquetting mould. Briquettes were produced at a pressure of 10.4 kg/cm² and samples were replicated 4 times. The briquettes were labelled as Sterculia Briquette (SB), Anthocleista Briquette (AB), and Trichilia Briquette (TB). Weight, length and thickness of each briquettes were recorded before drying. The data collected were subjected to statistical analysis (ANOVA at $p<0.05$). The physico-mechanical properties of extractive-free wood briquette in all the species increased with increase in binder level. They gave highest value at 15g binder level. Their values ranged from 0.67 to 0.89g/cm^3 for density, 71.55 to 99.91% for shatter index and 11.16 to 29.34N/mm^2 for compressive strength. However, combustion properties of the briquette show that ash content increased with increase in binder level and ranged from 2.12 to 5.75% while calorific value decreased with increase in binder level with range of values from 32.51 to 33.40MJ/kg^1. Anthocleista briquette performed best at 15g binder level in physico-mechanical properties while Trichilia briquette at lowest binder level (5g) is preferable in terms of combustion properties. Removal of extractive was observed to improve the calorific value of the briquette.

KEYWORDS: *Binder level, Calorific value, Characterization, Physico-mechanical, Sawdust,*

INTRODUCTION

The use of wood fuel is increasingly scarce and expensive because the current rate of deforestation is not proportional with the rate of afforestation due to urbanisation and the use of wood for building and manufacturing of wood based products (Aliyu *et al.*, 2021). The swift growth in human population and activities tend to yield in tremendous increase for energy and a corresponding rise in waste generation (Temesgen *et al.*, 2022). According to report, Nigeria generates about 42 million tons of residues on average per year (MacMillan and Turrentine, 2017). The majority of these wastes are either burnt at refuse sites or dumped on farmlands, endangering the environment and contributing to issues like soil erosion and global warming (USPR,

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2021). Currently, studies have shifted their interests to biomass as a good substitute energy source for reducing the usage of fossil fuels and the ensuing greenhouse gas emissions (World Bioenergy Association, 2019). This is gradually shifting the interest of developing countries from the conventional use of woody based fuels for cooking and other heating purposes. Thus, alternative sustainable energy sources are required, particularly in these regions. Large-scale energy generation from this agro-waste can sustain energy needs in rural regions while helping to clean up the environment, particularly from agro-activities, and preserving space that would have been utilized as a dump (Davies and Abolude, 2013). Therefore, biomass feedstock is an essential renewable source. Byproducts including ethanol, biogas, biodiesel, and densified solid fuel can be produced from biomass feedstocks. Densified solid fuel, commonly referred to as biomass briquetting, doesn't require sophisticated technology, it's the most straightforward and easy method of using bioresources. A number of research have used various pressure circumstances to experimentally examine the properties of alternative biomass briquettes made from wood residues (Xinyi *et al.,* 2023; Ajimotokan *et al.,* 2019, Anguruwa *et al.,* 2014). Higher density briquettes made from these residues can be used in place or in addition to solid fuels like coal, firewood, and charcoal.

With the objective of enhancing the solid fuel's calorific, mechanical and physico-chemical characteristics, certain chemical composition of the biomass capable of negatively influencing its performance should be considered. Chemical composition of wood comprises of cellulose, hemicellulose and lignin alongside many other organic compounds (extractives). They make up a minor portion of the wood's composition and can be extracted using hot water or organic solvents (Koch, 2006). With the exception of certain tropical and subtropical woods, which have much higher extractive contents (up to 20%), wood extractives typically do not exceed 5% of the dry wood mass. The solubility of extractives in wood has its own importance and, consequentially, in industrial applications. For example, the oxidation of extractives leads to an increased acidity of the wood, thereby encouraging its deterioration (Shebani *et al.,* 2008). An extractive-free residue lowers the fixed carbon content, which decreases the production of charcoal and causes the thermo-gravimetric curve to shift to higher temperatures (Várhegyi *et al.,* 2004). Thus, eliminating these wood extractives have to be regarded as pretreatment in order to guarantee briquette quality and performance. The benefits of using biomass briquettes over charcoal have been investigated and reported by several authors (Xinyi *et al.,* 2023; Lubwama and Yiga, 2020; Ikelle *et al.,* 2017), along with the advantages over traditional firewood.

The type of biomass and compression level combine to give briquettes its physical properties and combustion rate improving their quality. The compression properties depend on the type of binders and ratio used in the briquette production. The addition of binders (either organic or inorganic) tend to have a positive outcome on the strength property of briquettes (Abedeen, 2012). Thus, physical properties such as durability, compressive strength, hardness, density and the calorific value should be put into consideration. Else, they lose their quality after exposing themselves to handling, transportation or storage. With this in mind, this study is focused on production of briquettes from sawdust obtained from three wood species using gum arabic as a binder, to investigate the effect of gum-arabic binders on the strength characteristics of the briquette, and in terms of combustions efficiency such as calorific value, volatile matter, flame temperature, boiling time and specific fuel consumption for use as solid fuel materials.

MATERIALS AND METHODS

Source Wood Residue and Briquette Production

Extractive-free residue of *Sterculia tragacantha, Anthocleista vogelii,* and *Trichilia spp* were collected from Forestry Research Institute of Nigeria (FRIN). The samples were air dried and sieved using 2mm sieve in order to reduce particles size. The quantity of starch was varied (5, 10 and 15g) while 100ml of boiled water at 100°C was used to prepare gum-arabic to form gelatin/paste (Aransiola *et al*., 2019). For each batch of briquettes, 50g of sawdust was mixed with starch until a uniform mixture was obtained. The mixture was hand-fed into the mould and compacted at a pressure of 10.70 $kg.cm^{-2}$ for 5 min before the briquette was removed, and samples were replicated 4 times (Figure 1). However, the suitability of the briquettes for handling, transportation and cooking (physico-mechanical and combustion properties) were determined.

Characterisation of Briquettes

The physico-mechanical and combustion properties were carried out following the standards methods in Table 1.

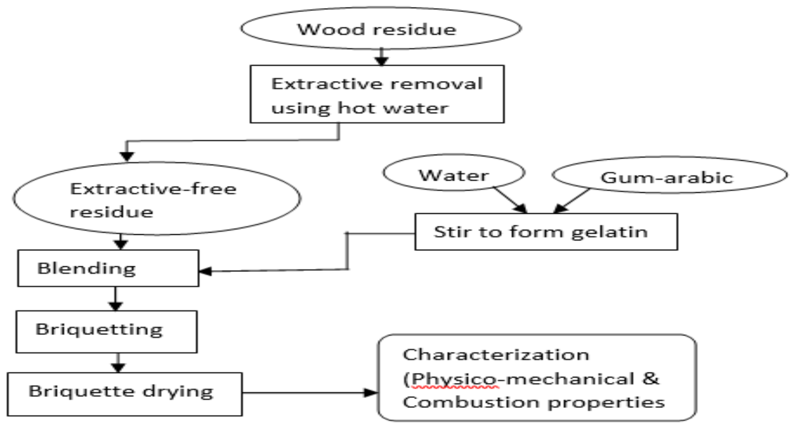

Figure 1: Schematic for Briquette Production.

Table 1: Method of determination of physico-mechanical and combustion properties of briquette

Parameters	Methods
Density (g/cm^3)	ASTM Standard D2395-17 (2017)
Dimensional stability (mm)	Length was being measured at intervals of 0, 30, 60, 1440, and 10,080 minutes. (Olorunisola , 2007; Sotannde *et al*., 2010)
Shatter Index (%)	ASTM Standard D440-86 (2002).
Compressive strength (N/mm^2)	ASTM Standard D2166-85 (2008).
Volatile Matter (%)	ASTM Standard D3174-12 (2018)
Ash Content (%)	ASTM Standard D3175-20 (2018)
Fixed Carbon (%)	ASTM Standard D3172-13 (2021)
Calorific Value (MJ/kg^1)	ASTM Standard D5865-13 (2013)

Experimental Design

This is a 3 x 3 factorial experiment in a completely randomized design (CRD). The experiment was replicated three (4) times which amounted to a total of 36 samples. The statistical model:

$$Yijkl = \mu + Ai + Bj + (AB)ij + Eijk \quad (1)$$

Where: Yijk=Individual observation
μ = General mean
Ai = Effect of factor A (Species)
Bj = Effect of factor B (Binder level)
(AB)ij = Effect of Interaction AB
Eijkl= Experimental Error

Statistical Data Analysis

All significance tests in this study were conducted at $p < 0.05$. Duncan's Multiple Range Test (DMRT) is a post-hoc statistical method used to compare the various treatment means in an experiment. Its primary function is to identify which treatment means are significantly different from each other after an analysis of variance (ANOVA) has indicated significant differences (Duncan, 1955). In this study, DMRT was employed to examine significant differences between each species and binder level for all parameters.

RESULTS AND DISCUSSION

Physico-Mechanical Properties

Density

The briquetting process is characterised by density which is an essential parameter. The mean densities of extractive-free briquette samples are shown in Fig. 2. They were in the range of 0.67 to 0.89 g/cm3. The analysis of variance in Table 2 shows that there is significant difference in the density at the different binder level and among the different briquettes types. It was observed from Table 3, that as the quantity of binder increases the density of the briquettes also increases. Variation based on binder level shows that briquette bonded with 15g binder are significantly different from those bonded with 5 and 10g binder level. However, the compressive strength of the different briquettes (SB, AB and TB) differs significantly. The energy/volume ratio increases with increasing density Mulu et al., (2024). The density for Milicia excelsa ranges of 0.27 to 0.53g/cm3 was obtained by Tomen et al., 2023. The values obtained are higher than those of Mfomo et al., (2020) on medium-heavy woods. The highest density in this study is within the value for those [0.470 - 0.851] of

(Bot et al., 2021). The high density obtained in this study could be as a result of the materials used in the production.

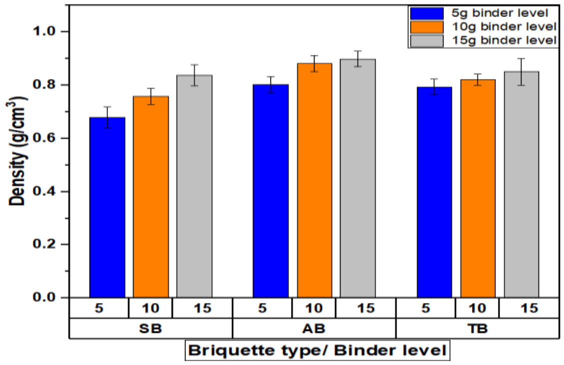

Figure 2: Grouped Columns Plot for Density Based on Binder Level and Briquette Type

Table 2: Anova Result for Physico-Mechanical Properties

Source variation	Df	Sum of square	Mean square	Sig.
Density (g/cm^3)				
Species	2	0.06929	0.03464	0.000077*
Binder level	2	0.03803	0.01902	0.002512*
Species*Binder level	4	0.04171	0.01043	0.009721*
Error	27	0.06815	0.00252	
Total	35	0.21717		
Shatter index (%)				
Species	2	705.0	352.5	0.000000*
Binder level	2	854.7	427.3	0.000000*
Species*Binder level	4	2501.9	625.5	0.000000*
Error	27	303.2	11.2	
Total	35	4364.8		
Compressive strength (N/mm^2)				
Species	2	839.05	419.53	0.000000*
Binder level	2	997.75	498.88	0.000000*
Species*Binder level	4	639.06	159.76	0.000000*
Error	27	15.27	0.57	
Total	35	2491.12		

*= Significant (P<0.05), ns= not significant (p>0.05), Df = Degree of freedom

Table 3: Follow-up on Test of Significance for Physico-Mechanical Properties

Source of variation	Density (g/cm^3)	Shatter index (%)	Compressive strength (N/mm^2)
Binder level			
5g	0.78[a]	87.52[a]	15.01[a]
10g	0.80[a]	88.02[a]	19.81[b]
15g	0.86[b]	98.10[b]	27.78[c]
Briquette type			
SB	0.75[a]	97.35[b]	23.78[b]
AB	0.86[b]	89.20[a]	14.06[a]
TB	0.82[c]	87.09[a]	24.76[c]

SB=Sterculia Briquette, AB=Anthocleista Briquette and TB=Trichilia Briquette. Values with the same alphabets are not significantly different.

Shatter index

The binding strength between the briquettes constituent elements determine its durability Mulu *et al*., (2024). The shatter of extractive-free briquette samples is shown in Fig. 3. The shatter index of the briquettes was in the range of 71.55 to 99.91 g/cm^3.The analysis of variance in Table 2 shows that there is significant difference in the shatter index at the different binder level and among the different briquettes types. It could be observed from Table 3 that as the quantity of binder increases the shatter index of the briquettes increases. Variation based on binder level shows that briquette bonded with 15g binder are significantly different from those bonded with 5 and 10g binder level. Likewise, the shatter index of SB briquette is significantly different from AB and TB. A durability rating of 80–90% is regarded as good while anything higher than 90% is considered very good (Okia, 2016). Shatter index of 90% for briquettes produced from other sawdust, as compared to the produced briquette was reported by Aliyu *et al*., (2021). The high durability of the briquette in this study could be as a result of the type of binder (gum-arabic) used.

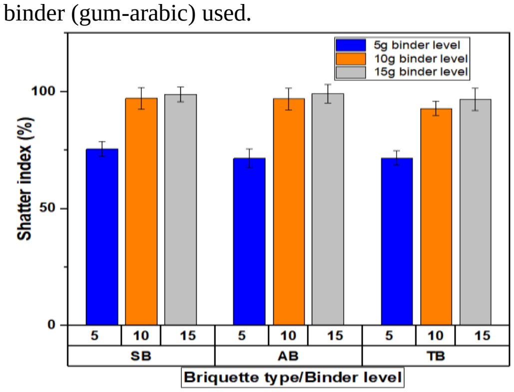

Figure 3: Grouped Columns Plot for Mean Shatter Index Based on Binder Level and Briquette Type

Compressive Strength

The Compressive strength of extractive-free briquette samples is shown in Fig. 4. The Compressive strength of the briquettes was in the range of 11.16 to 29.34N/mm^2.The analysis of variance in Table 2 shows that there is significant difference in the Compressive strength at the different binder level and among the different briquettes types. It could be observed from Table 3, that as the quantity of binder increases the Compressive strength of the briquettes increases. When the binder level was varied, it was observed that the compressive strength of the 3-binder level is significantly different from each other. Similarly, the compressive strength of the different briquettes (SB, AB and TB) differs significantly. Compressive strength shows the highest crushing load a briquette can withstand before cracking or breaking (Mutu *et al*., 2024). The produced briquette has better compressive strength compared to that of the briquette produced by Mitchual *et al.*, (2013). In their study, Ezenwa *et al.*, (2024) recorded a compressive strength of 8.31N/mm^2 for breadfruit pulp (non-wood). Other factors that influence the strength of briquettes are compaction pressure, material type, binder type, binder proportion and particle size (Gendek *et al*., 2018).

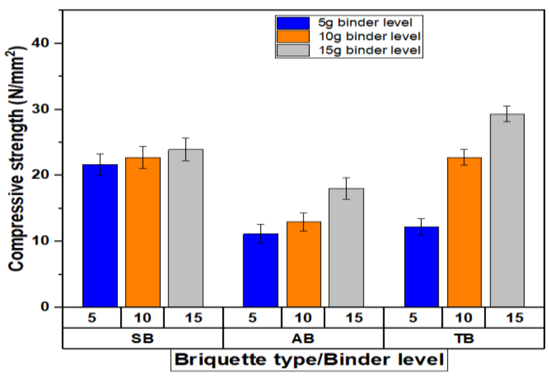

Figure 4: Grouped Columns Plot for Mean Compressive Strength Based on Binder Level and Briquette Type

Stability Rating

Figure 5a, b, and c shows the stability trend of St, Av, and Ts respectively. Linear expansion of AB briquettes (Fig 5c) was observed to be minimal because it showed better stability than SB and TB (Fig 5a and c). This diameter and height of the briquettes were measured immediately after production, after intervals of time according to Jiao *et al.,* (2020). When the stability trend was observed among the three binder level, it shows that briquette produced at with 5g binder exhibit best dimensional stability with time. This is because it tends to be more linear with minimal expansion, it gave a nearly straight line after 30mins of production. This confirms that stability of the briquette is a function of the binder levels and density (Suparin *et al.*, 2008). Also, Kaliyan *et al*., (2009) reported that dimensional stability was mainly dependent on feed stock, binder type and compression pressure. Suparin *et al*., (2008) recorded that gum arabic bonded briquette is more stable than starch bonded briquettes. This difference could be attributed to the difference in the materials used for the briquettes. The stability trend in this study is in line with the trend recorded by Sotannde *et al.,* (2010).

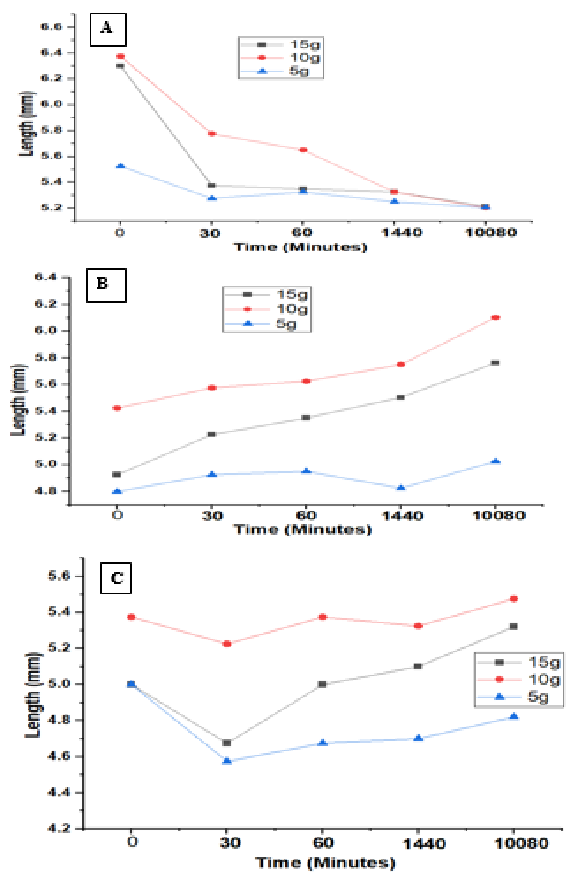

Figure 5: Line Plot Showing Variation in Stability (linear expansion) of Briquettes (a) SB (b) AB (c) TB

Combustion Properties

Volatile Matter

The volatile matter of the briquettes made from extractive-free residue ranged from 14.50 -27.00%. The minimum volatile matter was obtained in TB at 15g binder level while the highest was obtained in AB at 5g binder level (Figure 6). Analysis of variance in Table 4 shows that binder level significantly influenced the volatile matter of the briquettes. Follow-up test in Table 5 indicated briquettes produced at 15g binder level is significantly different from those produced at 5 and 10g binder level. It also shows that volatile matter decreases with increase in binder level. Higher VM is a sign of the readiness of the briquettes to ignite during combustion, and greater mass loss might be experienced during carbonization when the VM is high Waheed *et al*., (2023). It also shows that more energy is taken when the volatiles are burnt off before the release of heat energy Onukak *et al*., (2017). According to study by Chungcharoen and Srisang, (2020) who noted that the high volatile matter caused the briquettes to burn. Additionally, as the content of volatile matter in briquettes increases, the amount of gaseous emission also increases during combustion. This means that the amount of gaseous emissions in this study will be low because the volatile matter is low.

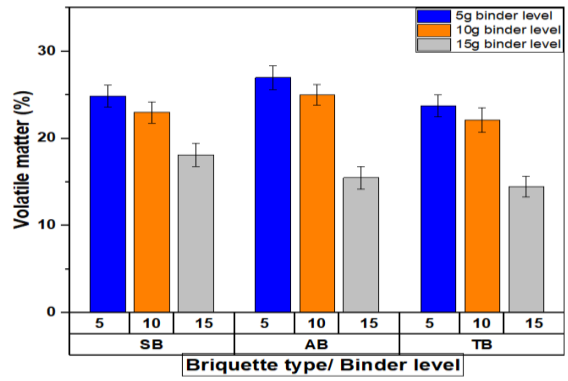

Figure 6: Grouped Columns Plot for Mean Volatile Matter Based on Binder Level and Briquette type

Table 4a: ANOVA Result for Combustion Properties

Source variation	Df	Sum of square	Mean square	Sig.
Volatile matter (%)				
Species	2	37.63	18.81	0.267151
Binder level	2	208.50	104.25	0.002282*
Species*Binder level	4	385.75	96.44	0.000480*
Error	27	366.31	13.57	
Total	35	998.19		
Ash content (%)				
Species	2	37.8176	18.9088	0.000000*
Binder level	2	9.0134	4.5067	0.000036*
Species*Binder level	4	1.0077	0.2519	0.502831
Error	27	7.9491	0.2944	
Total	35	55.7877		
Fixed carbon (%)				
Species	2	113.8	56.9	0.028097*
Binder level	2	135.6	67.8	0.015603*
Species*Binder level	4	387.6	96.9	0.000550
Error	27	375.8	13.9	
Total	35	1012.9		
Calorific value (MJ/kg^1)				
Species	2	2.313021E+08	115651068	0.066710
Binder level	2	2.313376E+08	115668801	0.066685
Species*Binder level	4	4.627223E+08	115680584	0.036043
Error	27	1.041561E+09	38576347	
Total	35	1.966923E+09		

*= Significant (P<0.05), ns= not significant (p>0.05), Df = Degree of freedom

Table 5: Follow-up on Test Significance for Combustion Properties

Source of variation	Volatile matter (%)	Ash conten t (%)	Fixed carbon (%)
Binder level			
5g	22.29[a]	3.20[a]	15.01[a]
10g	24.04[a]	3.25[a]	19.81[b]
15g	18.29[b]	4.29[b]	27.78[c]
Species			
SB	-	5.00[c]	73.00[a]
AB	-	3.13[b]	74.36[ab]
TB	-	2.61[a]	77.26[b]

SB=Sterculia Briquette, AB=Anthocleista Briquette and TB=Trichilia Briquette. Values with the same alphabets are not significantly different.

Ash Content

Ash content determination is vital for assessing the quality and efficiency of briquettes as a fuel source (Ogunjobi *et al.*, 2022). From Fig 7, it was found that the maximum percentage of ash content was found to be 5.75% for the SB sample at 15g binder level and the minimum percentage of ash content was recorded as 2.12% for the TB sample at 5g binder level. It was observed in Table 4 that ash content of the extractive free briquettes was significantly affected by both the species and binder level. However, the percentage of ash content increases with increase in binder level Table 5. The (ISO, 2014) standard recommends a minimum value of 6% and a maximum value of 10% for ash content, however, the ash content in this study falls within the requirement. Sawadogo *et al.*, (2018), reported that it is disadvantageous to have high concentrations of ash, because it can contribute to dust and toxic substances in the environment. Similarly, briquette ash content generally causes an increase in the combustion residue, as ash reduces the briquette heating effect (Sotannde *et al.*, 2010). For combustion efficiency, lower ash content is most preferable to avoid slagging, and it also allows for air to penetrate the stove, thereby accelerating burning rate. The removal of extractive in this study could have contributed to the lower ash content of the briquettes.

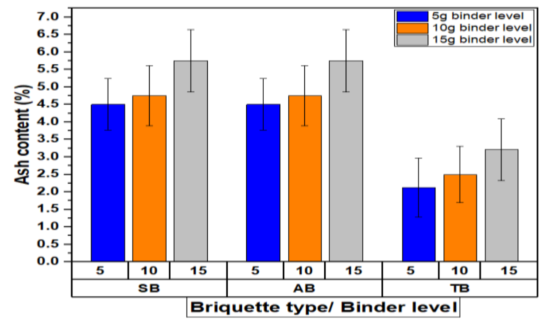

Figure 7: Grouped Columns Plot for Mean Ash Content Based on Binder Level and Briquette Type

Fixed Carbon

Fixed carbon content is a parameter that influences the stability and characteristics of the flame of a fuel material during combustion (Falemara *et al.*, 2018). The fixed carbon content of the fuel is the percentage of available carbon for the combustion process. The highest percentage of fixed carbon content value was found to be 82.29% for the TB sample at 15g binder level, and the lowest fixed carbon content of 69.37% was recorded for SB briquette at 5g binder level. Table 4 shows that both the species binder level significantly influence the fixed carbon of the extractive-free briquettes. It was observed that fixed carbon in all the samples increased with increase in binder level Table 5. The maximum fixed carbon content obtained in this current study is higher than 71.40 obtained in Helwani *et al.*, 2020. The result shows that fixed carbon increased with decrease in volatile matter (Kpalo *et al.*, 2021). Fixed carbon content of briquettes can be as high as 90% in according to Onukak *et al.*, (2017) or as low as 5% as reported by Onochie *et al.*, (2017).

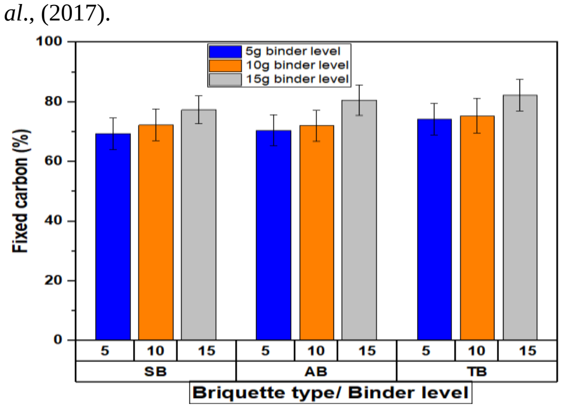

Figure 8: Grouped Columns Plot for Mean Fixed Carbon Based on Binder Level and Briquette Type

Calorific Value

The calorific value of extractive-free briquettes was found, and the mean values were presented in Fig 9. The highest value was obtained in TB briquettes, and it was found to be 33.4 MJ/kg^1 at 5g binder level, whereas the lowest value was recorded for SB briquettes, and it was found to be 32.51 MJ/kg^1 at 15g binder level. Table 4 shows test of no significance difference while the trend in Table 5 shows that calorific value decrease with increase in binder level. The produced briquette showed better calorific value compared to Malika *et al*. 2015 that reported calorific value of 21.26 MJ/kg for Holey bio-briquettes. The maximum heating value for all the briquette are higher than recommended minimum requirement of 14.5 MJ/kg by ISO, (2021). The obtained values are higher than the average value range of 18-21 MJ/kg reported in (Chungcharoen and Srisang, 2020). High calorific value obtained in this study could be as a result of the extractive that was removed.

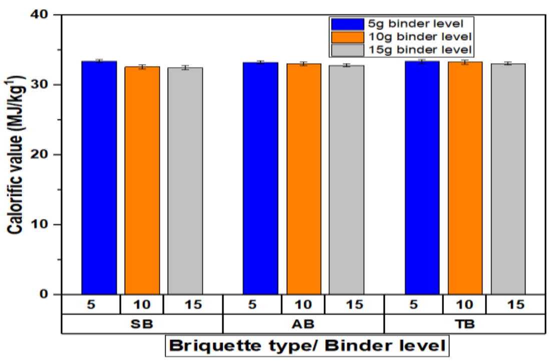

Figure 9: Grouped columns plot for mean calorific value based on binder level and briquette type.

CONCLUSION AND RECOMMENDATIONS

The investigation revealed that fuel briquettes produced from extractive-free residue of *Sterculia tragacantha, Anthocleista vogelii,* and *Trichilia spp* are good for briquettes production. Anthocleista briquette performed best at 15g binder level in Physico-mechanical properties, which is an indication that increase in binder level tends to increase the density and strength properties of briquette. While Trichilia briquette at the lowest binder level (5) is preferable in terms of combustion properties. Removal of extractive was observed to improve the calorific value of the briquette for house hold cooking and for sustainable environment. The research recommended that further research be carried out on the cooking efficiency of the briquettes such as water boiling test, Fuel burning rate, Specific fuel consumption, Thermal fuel efficiency etc.

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Authors contributions

Authors AGT managed data collection, interpretation of data, writing of manuscript, material support, and review of manuscripts and wrote the first draft of the manuscript. Authors OCA and AIT managed the literature searches. Author AAA, AOA and KMI managed the development of methodology, data analysis, and the development of the model. All authors read and approved the final manuscript.

Ethics Committee Approval: N/A.

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