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Fuel Properties of Briquettes Made from *Acacia Mangium* Pods and Plantain (*Musa Paradisiaca*) Peduncles with Cassava Starch Binder

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Abstract. *This study investigated the use of cassava starch as a binder in producing briquettes from Plantain peduncles and Acacia mangium pods, focusing on their fuel properties and the effects of binder viscosity (8 cP, 14 cP, 29 cP) and quantity (30 g, 50 g, 70 g) on physico-mechanical characteristics. Acacia mangium pods showed superior fuel properties, including higher gross calorific value (17.68 ± 0.13 MJ/kg), lower ash content (3.60%), and higher volatile matter (90.35%) compared to Plantain peduncles (12.58 ± 0.37 MJ/kg, 31.60%, and 63.67%, respectively). Conversely, Plantain peduncle briquettes exhibited better mechanical properties, including higher relaxed density (504.09 – 565.17 kg/m^3), compressive strength (8.50 – 19.99 N/mm), and impact resistance index (166.66 – 500%). In contrast, Acacia mangium briquettes were more prone to expansion, with greater increases in length (16.35 – 42.13%) and diameter (0.88 – 2.45%) compared to Plantain peduncles (1.43 – 30% and 1.06 – 2.16%). Statistical analysis confirmed significant ($p < 0.05$) effects of binder properties on briquette performance, revealing distinct influences for each biomass type, with more complex interactions for Acacia mangium. Optimizing binder characteristics improves briquette quality, demonstrating the potential of both biomass types for sustainable fuel production.*

Keywords: Plantain peduncles, *Acacia mangium* pods, binder viscosity, binder quantity and centipoise (cP)

Introduction

Escalating global consumption of fossil fuels has exacerbated climate change and posed significant risks to public health [1]. As a critical input for manufacturing and service sectors, energy supply profoundly influences societal dynamics, including political and security landscapes [2]. Uncontrolled anthropogenic activities, including deforestation and industrialization, have led to a substantial accumulation of atmospheric carbon, posing a critical threat to planetary health [3]**.** Deforestation, primarily driven by reliance on firewood in developing countries, has severe environmental and human health consequences, including chronic lung diseases [4]. Fostering healthy living and a sustainable environment necessitates transitioning to clean, renewable energy sources [2]. Bioenergy emerges as a viable alternative within the framework of a green economy due to its potential to mitigate resource depletion and enhance environmental sustainability [5]. The Paris Agreement of 2015 solidified global efforts to fight climate change by limiting global temperature rise to below 2 °C [6]. Diversifying energy sources is imperative to fulfill the goals of this agreement. The detrimental environmental and health impacts of fossil fuels have spurred significant investments in renewable energy research and development [7]. According to Oumarou et al. [8], energy is fundamental to human life, underpinning activities from basic sustenance to complex industrial processes. The cost, accessibility, and ecological consequences of energy sources are global concerns as the search for sustainable alternatives intensifies. The principal energy supply comes from non-renewable sources such as oil, natural gas, and coal, which contribute to these sources' scarcity and global warming. The predominant reliance on non-renewable fossil fuels exacerbates resource scarcity and climate change.

Energy security and climate change concerns have intensified calls for energy diversification. Biomass, a renewable and environmentally friendly resource, has emerged as a promising alternative [9]. Efforts to optimize the conversion of agricultural residues into cost-effective energy products are gaining currency to address global energy demands [10]**.**

Ghana's reliance on natural forests for fuelwood is substantial, accounting for approximately 90% of consumption [11]. Taiwo and Oluremilekun [12] states that**,** despite the annual generation of 140 billion metric tonnes of biomass through agriculture, their underutilization poses environmental and health risks when improperly managed. Densification processes can enhance these residues' handling, transportation, and storage. Agricultural residues, particularly cassava, maize, oil palm, Plantain, rice, and sorghum, hold significant energy potential, estimated at 1.09 EJ [13]. The production of briquettes from loose biomass, including agricultural and forestry residues, will play a pivotal role in the global renewable energy agenda [7].

Ghana holds a prominent position in Plantain production, ranking as the foremost producer in West Africa and the second in Africa, following Uganda and Rwanda [14]. In 2016, Ghana's Plantain production reached approximately 3.95 million metric tons, contributing significantly to the agricultural Gross Domestic Product (GDP) at 13.1% [15]. This substantial production generates considerable agricultural residues, with *Musa Paradisiaca* accounting for about 59% of the total crop residues produced in the country [16]. Among these residues, Plantain stalks are particularly voluminous and abundant [17]. Given this context, exploring the potential [18] utilization of fiber derived from Plantain peduncles for briquette production presents a promising avenue for developing alternative energy sources

Acacia mangium possesses a calorific value ranging from 4800 to 4900 Kcal/kg, making it a promising source of firewood and charcoal [19]. *Acacia mangium* is noted for its rapid growth and adaptability, which is why it is promoted for forest plantation development in Ghana. Moreover, its role in ecological restoration is evident, as it is commonly employed to rehabilitate degraded mined lands [20] as an exotic tree species for Forest Plantation Development in Ghana**.** Afrifa [21] reported that *Acacia mangium's* utility extends beyond the main stem and branches, as local populations use fallen debris and dried pods as fuel.

Briquette production in Ghana has not received enough attention [22]. To commercialize briquette production, we need to enhance briquetting technologies that utilize various biomass materials, such as agricultural residues (rice husks, corn stalks), forestry waste (sawdust), and urban waste (paper). Successful briquettes should have high density, low moisture content, high calorific value, low ash content, and consistent burning properties.

This study innovatively investigated using Plantain peduncles and *Acacia mangium* pods, combined with cassava starch as a binder, to produce briquettes from underutilized agricultural waste. The research addressed critical gaps in comparative fuel characteristics, binder optimization, and sustainability assessment by focusing on these biomass sources. This thorough examination of fuel properties and energy efficiency highlights the potential to transform residues from biomass types into alternative cooking fuel, significantly contributing to sustainable development and local energy solutions in regions rich in agricultural by-products. Plantain peduncles are abundant agricultural waste with high fiber content, while *Acacia mangium* pods provide good calorific value and combustion properties, presenting innovative possibilities for briquetting research. Cassava starch serves as an ideal binder due to its strong adhesion, local availability, cost-effectiveness, and biodegradability. This combination offers a unique opportunity for waste utilization, sustainable energy production, and rural development, while also addressing the knowledge gap in biomass briquetting technology.

Theoretical Background

Biomass is a viable alternative to fossil fuels, offering an abundant and renewable energy source [23]. Among its applications, briquettes made from compressed agricultural residues have gained interest for their potential to reduce environmental pollution, utilise agricultural by-products, and provide cost-effective energy [24]. Although materials such as Plantain peduncles and *Acacia mangium* pods are underutilized in briquette production, their lignocellulosic properties enhance combustion, making Acacia mangium pods, in particular, rich in carbon and possessing a moderate calorific value, effective energy source [25]. Plantain peduncles, by-products of Plantain cultivation, contain cellulose, hemicellulose, and lignin, which improve binding and combustion efficiency [26].

In the briquetting process, cassava starch acts as a natural binder, enhancing the mechanical strength of briquettes through gelatinization [27]. The binder's proportion and viscosity critically influence briquette quality. While a higher binder content can improve compressive strength and durability, it may also reduce calorific value by decreasing biomass content [28]. Additionally, viscosity affects the binder's flow and capacity to uniformly coat biomass particles [25]. This study examines how binder quantity and viscosity variations can optimise briquettes' physic-mechanical and combustion properties.

For briquettes to be classified as high-quality, they should maintain significant density, durability, compressive strength, and favourable fuel characteristics such as high calorific value, low ash, and moisture content [29]. The interaction between biomass and binder properties is crucial for achieving these criteria, underscoring the significance of binder characteristics in this research.

Moreover, the composition and quality of briquettes considerably influence their thermodynamic and combustion behaviour. Optimal binder levels can enhance combustion efficiency, reflected in higher burn rates and reduced emissions [30]. This research aims to deepen our understanding of sustainable fuel production by investigating the impacts of varying cassava starch levels and viscosities on briquette performance.

This study supports global sustainability efforts by promoting agricultural residues to reduce waste and greenhouse gas emissions while highlighting economic benefits for rural communities reliant on Plantain peduncles and *Acacia mangium* pod resources. Developing efficient and sustainable briquettes advances renewable energy solutions and aligns with environmental sustainability goals.

Materials and Methods

Materials and material preparation

Figure 1. Biomass and binder raw materials (a = Plantain peduncles, b = *Acacia mangium pods*, c = *cassava*)

Biomass and binder raw materials are shown in **Figure 1**. Plantain peduncles (stalks) were chopped into pieces, sun-dried on rubber mats for seven days, milled twice using a corn mill, bagged, and labeled. *Acacia mangium* pods were sun-dried for five days, milled, bagged, and labeled. The number of days for drying the materials depended on the environmental conditions (temperature and relative humidity) and the initial moisture content of the materials. Particles of Plantain peduncle and *Acacia mangium* pods were graded into particle size (P): $P \leq 2$ mm, using a sieve size of 2 mm and a diameter of 22 mm (BS/ISO.3310 Serial Number 20031797) [31].

Binder (cassava starch) preparation and mixing

Cassava starch was prepared according to [16]. Tubers of cassava were obtained, peeled, washed, and milled to obtain cassava dough**.** The dough was diluted with clean water to form a solution. After that, the solution was strained with 1mm wire mesh and stood for 24 hours to allow the starch to settle. The water was decanted to obtain the cassava starch, which was then dried for seven days to obtain powdered starch. The cassava starch powders of masses 100 g, 150 g, and 200 g were added to 1.5 L of water, respectively, ensuring the samples were formed without lumps and clogs. The binder solution was cooked/boiled for 10 minutes at 100 °C with continuous stirring until the whole paste was formed and cooled.

Determination of plastic viscosity of cooked cassava starch

The plastic viscosities of the cooked starch samples were measured using a Fann 35SA rotational viscometer according to ISO 10414-1:2008 [32]. The measurements were taken at ambient room temperature with a 250 g sample in a stainless steel cup. The rheometer's upper housing was tilted to position the cup correctly, and the rotor sleeve was adjusted to immerse the sample in the scribe line. After stirring for about 5 seconds, readings were taken at speeds of 6 RPM and then 3 RPM, allowing the dial to stabilize. The plastic viscosities were calculated using the formula:

$$Plastic\ viscosity\ (\mu_p) = 6\ RPM\ Reading - 3\ RPM\ Reading \tag{1}$$

Moisture content (MC)

Moisture contents of Plantain peduncle and *Acacia mangium* pods were determined per ASTM D4442-92 (2003) [33] using an oven-dry method per Moisture contents of the specimens were then computed as follows:

$$Moisture\ content\ (\%) = \frac{M_1 - M_0}{M_0} \times 100 \tag{2}$$

M_1 and M_0 are masses (g) of the test sample before and after oven drying, respectively, aspect ratio determination.

Fuel characteristics of biomass materials

Gross calorific value

The gross calorific value of the samples of biomass materials was determined in accordance with ASTM Standard E711-87: 2012 [34]. This was done using an adiabatic bomb calorimeter. About 0.4 g of each sample was burnt in the bomb calorimeter until complete combustion was obtained. The difference between the maximum and minimum temperatures obtained was used to compute the gross calorific values of the biomass materials as follows:

$$Q = \frac{(C_{water} + C_{cal})(T_2 - T_1)}{W_f} \tag{3}$$

The calorific value (Q) of a biomass sample was calculated using the following variables: sample weight (W_f), heat capacity of the bomb calorimeter (C_{cal}), rise in temperature (T_2–T_1), and heat capacity of water (C_{water}).

Proximate analysis

Percentage (%) ash content (PAC)

PAC of the biomass materials was determined in accordance with ASTM D 1102-84: 2008 [35]. This was done by heating approximately 2 g of oven-dried mass of each biomass material with a particle size of 425 µm in an electric furnace at a temperature of 600 °C for four hours. Thereafter, it was cooled in a desiccator and weighed to represent the ash content of the sample. The percentage ash content was calculated as follows:

$$Ash\ content\ (\%) = \frac{M_{ash}}{M_{oven-dry}} \times 100 \tag{4}$$

Where M_{ash} is the mass of the ash and $M_{oven-dry}$ is the mass of the oven-dried sample.

Percentage (%) volatile matter

Volatile matter content was determined using ASTM E872-82 (2013) [36]. The Weight of the crucible was taken and recorded; 5 g of moisture-free biomass material was weighed using an electronic balance of accuracy of 0.1 g into the crucible. Thereafter, W_1 was determined by heating the 5 g of moisture-free sample in the crucible in a furnace at a temperature of 450 °C for 30 minutes and weighed after cooling in a desiccator. The volatile matter (%) was then calculated using the formula below:

$$Volatile\ matter\ (\%) = \frac{F}{G} \times 100 \tag{5}$$

F is the change in the weight of the material sample, and *G* is the weight of the moisture-free sample.

Fixed carbon content

Fixed carbon contents of the biomass types were determined in accordance with ASTM D3172 12 (2021) [37]. Ash contents and volatile matter in the biomass types were determined using standard protocols, and fixed carbon was calculated using the operation:

$$Fixed\ carbon\ (\%) = 100 - AC - VM \tag{6}$$

Where *AC* is the ash content, and *VM* is the volatile matter of the biomass types.

Percentage (%) organic carbon (POC)

Organic carbon content of the biomass materials was determined using ASTM D 1102-84 (2008) [38] and FAO Guide to Laboratory Test [39]. This was done by subtracting the mass (g) of ash from the oven-dry mass of the sample to obtain the mass (g) of the organic matter component. The percentage of organic carbon content was then estimated as follows:

$$Organic\ carbon\ content\ (\%) = \frac{M_{organic\ matter} \times 0.58}{M_{oven-dry}} \times 100 \tag{7}$$

Where $M_{organic\ matter}$ is the mass of organic matter, and $M_{oven-dry}$ is the mass of the oven-dried sample.

Ultimate analysis

Elemental constituents, namely carbon, hydrogen, oxygen, nitrogen, and sulfur, were determined through ultimate analysis. The nitrogen content of the samples was determined using the Kjeldahl method for quantitative Determination of nitrogen in chemical substances. The sulfur content was determined by the turbid metric method [40]. The hydrogen content was determined using the flame atomic absorption spectrophotometer model Accusys 211 from Buck Scientific. The carbon content of biomass materials used for this study was determined per ASTM D 1102-84 (2007) and FAO guide to laboratory establishment (2008).

Briquette production

Seventy grams (70 g) of graded pulverized Plantain peduncles and *Acacia mangium* pods were weighed using an electronic balance capable of weighing up to an accuracy of 0.01 g, respectively. Biomass was mixed manually with the prepared binder of the following plastic viscosities: 8 cp, 14 cp, and 29 cp, and binder masses of 30 g, 50 g, and 70 g solution to get a homogeneous damp mass and uniform size and filled into the mold.

The hydraulic press and a piston compressed the raw material mixed with cooked starch against the other end of the mold to form the briquettes at a compacting pressure level of 5 MPa. To allow for air escape, a clearance of about 0.1 mm was provided between the piston and the inner wall of the mold. Briquettes were sun-dried for one week to obtain stability and rigidity [41]. **Figure 2** and **Figure 3** show briquettes made from Plantain peduncles and *Acacia mangium* pods.

Figure 2. Plantain peduncles briquettes

Figure 3. *Acacia mangium* pods briquettes

Physico-mechanical properties

Briquette's stability in diameter and length

Briquette stability was determined according to [42]. Briquette stability was evaluated by measuring dimensions immediately after production and again after a four-day period, using a digital caliper at multiple points on each sample. Briquettes' stability was then computed as:

$$Stability\ in\ length\ (\%) = \frac{L_f - L_0}{L_0} \times 100 \tag{8}$$

Where, L_0 and L_f are lengths of briquettes immediately after removal from the mold and ninety-six hours, respectively.

$$Stability\ in\ diameter\ (\%) = \frac{D_f - D_0}{D_0} \times 100 \tag{9}$$

Where, D_o and D_f are diameters of briquettes immediately after removal from the mold and ninety-six hours, respectively.

Relaxed density

Relaxed density was measured after a 30-day period, following ISO 3131 1975 [43]. Briquette mass was determined using a precise electronic balance, while dimensions were measured at multiple points with a digital caliper. Relaxed density (*RD*) was then computed as:

$$RD\ (g/cm) = \frac{108000 \times M_{(g)}}{\pi[d_1(mm) + d_2\ (mm) + d_3\ (mm)]^2 \times [l_1(mm) + l_2(mm) + l_3(mm)]} \tag{10}$$

Where d_1, d_2, and d_3 are diameters (mm) measured at three different points on the briquettes. l_1, l_2, and l_3 are lengths (mm) measured at three different points on the briquettes. $M_{(g)}$ is the mass of briquette.

Compressive strength (CS) in cleft

Briquettes' compressive strengths were evaluated using a standardized method (ASTM D2166-85, 2008) [44] employing a high-capacity universal testing machine. Samples were subjected to horizontal compression at a controlled rate until structural failure occurred. The compressive strength in the cleft was then computed as follows:

$$Compressive\ strength\ in\ cleft\ (N/mm) = \frac{3 \times The\ load\ at\ the\ fracture\ point\ (N)}{[l_1\ (mm) + l_2(mm) + l_3(mm)]} \tag{11}$$

l_1, l_2, and l_3 were briquettes' lengths (mm) at points one, two, and three, respectively.

Impact resistance index (IRI)

Briquette durability was assessed via impact resistance testing, following ASTM D440 2007 protocol [45]. Samples underwent repeated vertical drops from a standardized height onto a rigid surface. Post-impact fragments were quantified, with significant pieces (≥5% of initial mass) used to calculate the impact resistance index. Impact Resistance Index (IRI) was then computed as follows:

$$IRI = \frac{N}{n} \times 100 \tag{12}$$

N was the number of drops, and *n* was the number of pieces that weighed 5% or more of the initial weight of the briquette after *N* drops.

Statistical analysis

Multivariate analysis (MANOVA) assessed the combined effects of binder viscosity and quantity on briquette properties. Subsequent univariate analysis (two-way ANOVA) was conducted to determine the individual and interactive impacts on specific briquette characteristics.

Results and Discussion

Table 1 summarizes the gross calorific values (GCV) and elemental (ultimate) and compositional (proximate) analyses of Plantain peduncles and *Acacia mangium* pods. The ultimate analysis reveals key elements-organic carbon, hydrogen, nitrogen, sulphur, and oxygen—that inform combustion characteristics and energy yield. The proximate analysis evaluates moisture content, ash, volatile matter, and fixed carbon, which are crucial for assessing the feasibility of these materials for briquette production and their potential as renewable energy sources.

Table 1. Fuel characteristics (ultimate and proximate analyses) of Plantain peduncle and *Acacia mangium* pods

Biomass	GVC (MJ/kg)	Ash (%)	VM (%)	OC (%)	FC (%)	H (%)	N (%)	S (%)	O (%)	MC (%)
Plantain peduncle	12.58 ± 0.37	31.60	63.67	35.11	4.73	11.52	1.70	0.18	19.89	9.8
Acacia mangium pods	17.68 ± 0.13	3.60	90.35	33.51	6.05	12.52	1.42	0.13	48.82	8.4

Calorific value

Calorific value, a critical parameter in assessing fuel quality, is the heat energy released per unit mass of a sample during complete combustion under constant oxygen volume conditions [46], [47]. Higher calorific values are a key criterion for the optimal performance of briquette fuel [18]. McKendry [46] posited that the energy content of biomass, on a dry, ash-free basis, generally falls within a narrow range of 17-21 MJ/kg across plant species used in his study. The present study's gross calorific value (GCV) analysis revealed distinct differences between the investigated biomass types. Plantain peduncle exhibited a GCV of 12.33 ± 0.37 MJ/kg, while *Acacia mangium* pods demonstrated a higher value of 17.68 ± 0.13 MJ/kg.

Comparative analysis with literature findings indicates that these values are lower than those reported by McKendry [46] for Pinus durangensis sawdust briquettes, which ranged from 19.35 to 21.63 MJ/kg. However, the GCV of *Acacia mangium* pods aligns closely with values reported by [47] for carbonized cocoa pods (18.472 MJ/kg and 16.731 MJ/kg). These findings suggest that while *Acacia mangium* pods exhibit promising energy potential, Plantain peduncles may require additional processing or blending to enhance their calorific value for optimal fuel applications.

Ash content

Ash content, representing non-combustible biomass components, varied significantly between Plantain peduncles (31.60%) and *Acacia mangium* pods (3.60%). The latter's ash content aligns with values reported for mahogany sawdust (1.3%), oak (3.4%), and gmelina (2.07%) by [10]. Grover and Mishra 1996 [24] noted that biomass fuels with > 4% ash content exhibit slagging behavior, though lower ash content doesn't preclude slagging entirely. Comparatively, in work [48] reported 20-40% of the ash content in loose biomass waste briquettes is lower than that of wood or coal.

Volatile matter

Volatile matter, comprising carbon, hydrogen, and oxygen components vaporizing upon heating [49], varied significantly between studied biomass types. Plantain peduncles exhibited a volatile matter content of 63.67%, lower than values reported for corn stover (66.93 ± 0.77%), switchgrass (79.53 ± 0.15%), and lodgepole pine (85.46 ± 0.26%) by [50]. In contrast, *Acacia mangium* pods demonstrated a notably high volatile matter content of 90.35%, surpassing not only the biomass mentioned above types but also exceeding values recorded by Chukwuneke et al. [10] for mahogany sawdust (83.1%), Gmelina (82.6%), oak (81.6%), and rice husk (73.4%). This high volatile matter content in *Acacia mangium* pods suggests potential advantages in combustion behavior and energy yield compared to other common biomass feedstocks.

Organic carbon, fixed carbon, hydrogen, sulfur, and oxygen contents

Table 1, columns 5 through 10, present the proximate analysis results for organic carbon, fixed carbon, hydrogen, sulfur, and oxygen content, respectively. Notably, Plantain peduncles exhibited a higher organic carbon content (35.11%) than *Acacia mangium* pods (33.51%). These findings align with the established correlation between elevated carbon content and increased heating value, as reported by Mitchual et al. [51].

Fixed carbon, a key parameter in biomass characterization, represents the residual char following the expulsion of volatile matter [52]. As detailed in **Table 1**, column 6, the fixed carbon content for the investigated Plantain peduncles and *Acacia mangium* pods was determined to be 4.73% and 6.05%, respectively. These values are significantly lower than those reported for coal and groundnut husk briquettes (16.77% - 53.22%) by [53], suggesting a disparity in the fixed carbon composition of biomass feedstocks.

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The fixed carbon content of Plantain peduncles and *Acacia mangium* pods is similar to that of briquettes made from coconut husk and other materials [54]. While higher fixed carbon content generally improves fuel quality, according to [18]**,** the hydrogen content in both biomass samples (plantain peduncles (11.51%) and *Acacia mangium* pods (12.52%)) is higher than the typical ranges between 5% to 6%, for biomass suggested by [49].

Nitrogen and sulfur content analysis

Table 1, Columns 8 and 9 present nitrogen levels for Plantain peduncles and *Acacia mangium* pods, respectively. Nitrogen levels in the biomass samples were within the range reported for other agro-residues in briquette production [55]. Sulfur content, while slightly higher than values reported for rice straw and sugarcane leaf briquettes [56], remained below the recommended threshold of 1% for minimizing environmental emissions [57]. These findings suggest that both biomass materials have the potential to be eco-friendly fuels, as low nitrogen and sulfur levels can mitigate the formation of harmful emissions and ash during combustion [56].

The relatively low nitrogen and sulfur content of the investigated biomasses is a critical factor in mitigating environmental impacts associated with combustion. Nitrogen oxide (NO_x) emissions, a primary concern in solid biofuel utilization, are linked to the fuel's nitrogen content [58]. Similarly, low sulfur content minimizes the release of sulfur oxides into the atmosphere, reducing potential air pollution [59]. These findings underscore the potential of these biomass materials as cleaner-burning alternatives.

Oxygen content, as determined for Plantain peduncles (19.89%) and *Acacia mangium* pods (48.82%), aligns with values reported in the literature [60]. Notably, higher oxygen content is often correlated with increased moisture content within the fuel. This phenomenon can adversely affect the fuel’s calorific value due to the formation of water vapor during combustion. Furthermore, elevated oxygen levels can increase carbon dioxide and water emissions, diminishing the fuel’s overall energy efficiency [61].

Physico-mechanical properties

Briquettes’ stability in length

Table 2. Change in length (%) of briquettes produced from Plantain peduncle and *Acacia mangium* pods at three viscosity levels (8 cp, 14 cp, and 29 cp) with varied binder quantities: 30 g, 50 g, and 70 g and particle size (*P*) $P \leq 2$ mm

Biomass	Binder Viscosity (cP)	Binder quantity (g) 30 g	50 g	70 g
Plantain peduncles	8	30.00	18.32	7.01
	14	23.33	6.75	1.43
	29	26.02	11.02	3.44
Acacia mangium pods	8	42.13	30.09	16.35
	14	38.51	22.64	12.34
	29	36.15	27.20	20.47

The findings reveal that all briquettes made from Plantain peduncles and *Acacia mangium* pods experienced a significant increase in length (see **Table 2**), ranging from 1.43% to 42.3%. Notably, Plantain peduncle briquettes had less elongation than those made from *Acacia mangium* pods. The influence of the binder quantity on the reduction of elongation is a significant discovery [62].

Briquettes made from *Acacia mangium* pods expanded the most. Those with a binder viscosity of 8 cP stretched the most, followed by those with 29 cP viscosity. A binder viscosity of 14 cP resulted in the least expansion for both *Acacia mangium* pod and Plantain peduncle briquettes. Using 70 g of binder led to the least elongation, while 30 g caused the most briquette expansion from both biomass types. Higher binder viscosity and lower binder content generally increased briquette elongation for both materials.

Briquettes' stability in diameter

Diameter stability, measured as post-production expansion percentage, significantly impacts briquette density and fuel quality. Excessive expansion compromises these properties [51]. **Table 3** shows the percentage changes in the diameter of briquettes made from Plantain peduncles and *Acacia mangium* pods.

Table 3. Stability in diameter (%) of briquettes produced from Plantain peduncle and *Acacia mangium* pods at three viscosity levels (8 cP, 14 cP, and 29 cP) with varied binder quantities: 30 g, 50 g, and 70 g, and biomass particle size (*P*) *P* ≤ 2 mm

Biomass	**Binder Viscosity**	**Binder Quantity**		
		30 g	**50 g**	**70 g**
Plantain peduncles	8	2.16	1.62	1.45
	14	1.23	1.06	1.43
	29	1.06	1.24	1.25
Acacia mangium pods	8	0.88	1.40	1.23
	14	1.05	1.92	2.45
	29	1.40	1.22	1.41

Higher viscosity binders led to increased briquette diameter, while lower viscosity binders resulted in decreased diameter. The average diameter change for briquettes with 8 cP viscosity binder was an increase of 1.71%, while for those with 29 cP viscosity binder, the average diameter change was 1.15%. Plantain peduncle briquettes exhibited superior compressive strength in the cleft, ranging from 8.50 to 19.99 N/mm, significantly higher than the 1.82 to 4.40 N/mm^2 range observed in *Acacia mangium* pod briquettes. This higher compressive strength in the cleft suggests that Plantain peduncles briquettes may be more durable and resistant to breakage during handling and transportation compared to *Acacia mangium* pod briquettes.

Plantain peduncle briquettes demonstrated superior relaxed densities (504.09-565.17 kg/m^3) compared to *Acacia mangium* pod briquettes (see **Table 4**). The highest densities (555.82-565.17 kg/m^3) were achieved with 29 cP binder viscosity, supporting previous findings on the positive relationship between binder viscosity and briquette density**.** Lower viscosities of 14 cP and 8 cP resulted in progressively decreased densities. *Acacia mangium* pod briquettes exhibited lower densities than the other biomass types. Additionally, there was an inverse relationship between the amount of binder used and the density of these briquettes, meaning that more binder led to lower density. This trend was particularly noticeable when using thicker binders.

Table 4. Relaxed Density (kg/m^3) of briquettes produced from Plantain peduncle and *Acacia mangium* pods at three viscosity levels (8 cP, 14 cP, and 29 cP) with varied binder quantities: 30 g, 50 g, and 70 g, and biomass particle size (*P*) *P* ≤ 2 mm

Biomass	Binder Viscosity	Binder Quantity		
		30g	50g	70g
Plantain peduncle	8	535.65	504.09	523.45
	14	537.57	538.10	518.15
	29	555.82	565.17	561.95
Acacia mangium pods	8	419.91	388.56	382.12
	14	422.47	387.44	378.56
	29	465.74	407.81	411.38

Impact resistance Index

Table 5. Impact resistance index (IRI) (%) of briquettes produced from Plantain peduncle and *Acacia mangium* pods at three viscosity levels (8 cP, 14 cP, and 29 cP) with varied binder quantities: 30 g, 50 g, and 70 g, and biomass particle size (*P*) *P* ≤ 2 mm

Biomass	Binder Viscosity	Binder Quantity		
		30g	50g	70g
Plantain peduncle	8	166.66	250.00	500.00
	14	166.66	250.00	500.00
	29	250.00	500.00	500.00
Acacia mangium pods	8	125.00	125.00	125.00
	14	125.00	125.00	166.66
	29	125.00	166.66	166.66

Table 5 shown *IRI* values escalated linearly with increasing binder content across all viscosities. For 8 cP viscosity, IRI jumped from 166.66% to 500% as binder content rose from 30 g to 70 g. At 14 cP *IRI* reached 250% at 50 g and plateaued. The highest viscosity (29 cP) yielded the most robust *IRI*, peaking at 500% for 50 g and 70 g binder contents. These findings unequivocally demonstrate a direct correlation between binder content and *IRI*.

Compressive strength (CS) in the cleft of briquettes

Table 6. Compressive strength in the cleft (N/mm^2) of briquettes made from Plantain peduncle and *Acacia mangium* pods at three viscosity levels (8 cP, 14 cP, and 29 cP) with varied masses of binder: 30 g, 50 g, and 70 g

Biomass	Binder Viscosity	Binder Quantity		
		30g	50g	70g
Plantain peduncle	8	8.50	11.93	13.98
	14	10.10	17.66	16.36
	29	9.63	19.99	16.68
Acacia mangium pods	8	2.72	2.37	1.82
	14	3.35	2.52	2.01
	29	4.40	3.15	2.76

One factor that enhances the longevity of briquettes is their strength [63]. **Table 6** presents the compressive strength in the cleft of briquettes produced. Plantain peduncle briquettes outperformed *Acacia mangium* pod briquettes in terms of compressive strength. The former exhibited a positive correlation between binder viscosity and compressive strength, with values ranging from 8.50 to 19.99 N/mm^2. Conversely, *Acacia mangium* pod briquettes displayed lower compressive strengths (1.82 to 4.40 N/mm^2) and an inverse relationship between binder content and compressive strength. Notably, the lowest compressive strengths were observed in *Acacia mangium* pod briquettes produced with 8 cP viscosity and 70 g binder content (1.82 N/mm^2). The compressive strength (*CS*) of *Acacia mangium* pod briquettes was influenced by both binder viscosity and quantity. Results indicate that briquettes with a higher binder viscosity (29 cP) exhibited superior *CS* to those with viscosity (14 cP). While increasing binder content within a specific viscosity generally led to slight improvements in *CS*, the effect was less pronounced than viscosity. Gendek et al. [62] reported compressive strengths of 9.69 MPa and 2.81 MPa for spruce and pine cone briquettes, respectively, providing a comparative framework for the current study's results. The results also indicated that *Acacia mangium* pod briquettes produced using a binder with viscosity 14 cP and binder contents 30 g, 50 g, and 70 g recorded *CS* in cleft ranging from 2.01 N/mm^2 to 3.35 N/mm^2, while those produced with a binder with 29 cP viscosity had *CS* in cleft that ranged between 2.76 N/mm^2 to 4.40 N/mm^2, the highest *CS* in cleft for *Acacia mangium* pod briquettes. Faizal et al. [41] concluded that briquettes with high compressive strength can be produced when biomass material with small particles is used and the briquetting process is performed at the highest temperatures. This corroborates [63] observation, which suggests that the finer the briquette particle, the smaller the pore spaces between the particles, and the more tightly the particles interlock, increasing the briquette's strength. Mitchual et al. [42] reported 9.69 MPa for the compressive strength of spruce briquettes and 2.81 MPa for pine cone briquettes.

Statistical Analysis

MANOVA results for Plantain peduncle *briquettes*

Table 7. Multivariate test results of binder properties on Plantain peduncle briquettes

Effect	Wilks' Lambda	F-value	Hypothesis df	Error df	Sig.	Partial Eta Squared
Intercept	0.000	31094.638	5.000	32.000	0.001	1.000
Binder viscosity	0.011	54.715	10.000	64.000	0.001	0.849
Binder quantity	0.003	113.664	10.00	64.000	0.001	0.947
Binder viscosity*Binder quantity	0.023	11.404	20.000	107.082	0.001	0.612

A multivariate analysis of variance (MANOVA) revealed significant main effects for binder viscosity and quantity on the combined dependent variables in the Plantain peduncle briquettes produced (see **Table 7**). For binder viscosity, the analysis yielded Wilks' Lambda = 0.011, F (10, 64) = 54.715, $p < 0.001$, with a substantial effect size (partial $\eta^2 = 0.895$). This indicates that binder viscosity profoundly influences the overall properties of Plantain peduncle briquettes. Similarly, binder quantity demonstrated a significant main effect with Wilks' Lambda = 0.003, F (10, 64) = 113.664, $p < 0.001$, and an even larger effect size (partial $\eta^2 = 0.947$), underscoring the effect of binder quantity on the characteristics of briquettes produced as supported by findings made by [7].

Bonferroni corrections post-hoc analyses result in significant effects of binder quantity on Plantain peduncle *briquette properties.*

Bonferroni corrections post-hoc analyses provided insights into the differences between binder viscosity and quantity levels (see **Table 8**). For binder viscosity, significant differences were observed between all pairs (14 cP, 29 cP, and 8 cP) for change in length ($p < 0.05$). The 8 cP viscosity differed significantly from both 14 cP and 29 cP regarding the change in diameter and compressive strength in the cleft ($p < 0.05$). For relaxed density, all pairs showed significant differences ($p < 0.05$), whereas for impact resistance index, 29 cP differed significantly from both 14 cP and 8 cP ($p < 0.001$).

With binder quantity, the analysis revealed significant differences between all pairs (30 g, 50 g, 70 g) for change in length and impact resistance index ($p < 0.001$ for all comparisons). Significant differences were found between 30 g and 50 g and 70 g ($p < 0 .001$) for compressive strength in the cleft, but not between 50 g and 70 g. Interestingly, despite the significant main effect for change in diameter, post-hoc tests did not reveal significant pairwise differences, suggesting that the effect may be subtle and only detectable when considering the overall pattern.

Table 8. Summary of significant Bonferroni post-hoc comparison

Dependent Variables	Binder Viscosity	Binder Quantity
Change in Length	All pairs	All pairs
Change in Diameter	8 cP vs. 14 cP, 29 cP	No Sig. differences
Relaxed Density	All pairs	No Sig. differences
CS in Cleft	8 cP vs. 14 cP, 29 cP	30 g vs. 50 g, 70 g
IRI	29 cP vs. 14 cP, 8 cP	All pairs

The higher viscosity binder (29 cP) consistently produced briquettes with greater relaxed density, compressive strength, and impact resistance. This suggests that a higher-viscosity binder might be preferable for applications requiring high durability and structural integrity, such as briquettes for high-stress environments or long-term storage. However, the trade-off is that higher viscosity also leads to greater changes in length, which could affect the dimensional stability of the briquettes. This could be a critical consideration in applications where precise dimensions are necessary, such as in automated handling systems or when uniform stacking is required. Conversely, lower viscosity binders (particularly 14 cP) result in smaller dimensional changes but with reduced mechanical strength. This could be advantageous in applications where maintaining precise dimensions is crucial or where the end-use of the briquettes does not demand exceptionally high strength or impact resistance. The quantity of binder used also plays a critical role in briquette properties. Increasing binder quantity generally leads to decreased changes in length, increased compressive strength, and higher impact resistance. However, the optimal quantity is not uniform across all properties or viscosities. For instance, compressive strength in the cleft tends to peak at moderate binder quantities (around 50 g) for all viscosities. At the same time, the impact resistance index continues to increase with quantity for lower viscosities but plateaus for higher viscosities. The observed interaction effects, particularly for relaxed density, compressive strength in the cleft, and impact resistance index, are paramount for Plantain peduncles briquette production. These interactions imply that the optimal binder quantity may differ depending on the viscosity used and the specific property being prioritized. For example, when using a high-viscosity binder (29 cP), a moderate quantity (50 g) may be sufficient to achieve maximum impact resistance. In contrast, lower viscosities may require higher quantities to approach similar performance levels.

MANOVA results on significant effects of binder quantity and viscosity of *Acacia mangium* pod briquettes

Multivariate analysis revealed statistically significant effects on binder properties and their interactions. **Table 9** shown Binder viscosity showed a significant effect (Wilks' Lambda = 0.164, F (10, 64) = 9.385, $p < 0.001$, partial $\eta^2 = 0.595$), indicating that the viscosity of the binder substantially influenced the physico-mechanical properties (stability in length, stability in diameter, relaxed density, compressive strength in cleft and impact resistance index). 59.5% effect size as indicated by partial eta squared and a smaller Wilks' Lambda value of 0.164 show huge differences between the groups. Comparably, binder quantity demonstrated significant effects on briquette properties (Wilks' Lambda = 0.026, F(10, 64) = 33.645, $p < 0.001$, partial $\eta^2 = 0.840$), suggesting that binder quantities used in producing the briquettes had huge effects (i.e., effect size of 84%) on the briquette properties as revealed by the value of the partial η2 = 0.840. The interaction between binder viscosity and quantity was also significant (Wilks' Lambda = 0.362, F (20, 107.082) = 1.922, $p = 0.018$, partial $\eta^2 = 0.225$), implying that the effect of binder quantity on the physical and mechanical properties varied depending on the viscosity of the binder used. Combined effects of the binder properties, as revealed by a lower *F*-value of 1.922 and an effect size of 22.5%, indicate that the effect is not as strong as compared to the effect the binder properties individually had on *Acacia mangium* pod briquettes' physical and mechanical properties.

Table 9. Multivariate Test results on how binder properties influence briquette properties

Effect	Wilks' Lambda	F-value	Hypothesis df	Error df	Sig.	Partial Eta Squared
Intercept	0.000	14954.892	5.000	32.000	0.001	1.000
Binder viscosity	0.164	9.385	10.000	64.000	0.001	0.595
Binder quantity	0.026	33.645	10.000	64.000	0.001	0.840
Binder viscosity*Binder quantity	0.362	1.922	20.000	107.082	0.018	0.225

Design: Intercept + Binder Viscosity + Binder Quantity + Binder Viscosity * Binder Quantity

Bonferroni-adjusted pairwise comparisons post-hoc analyses results for Acacia mangium pod briquettes.

Bonferroni-adjusted pairwise comparisons post-hoc analyses were conducted to examine specific differences between levels of binder viscosity and quantity (see **Table 10**). For binder viscosity, significant differences were found in the change in diameter between 8 cP and 14 cP ($p = 0.026$), with 8 cP resulting in smaller changes. Relaxed density and compressive strength in the cleft were significantly higher for 29 cP compared to 14 cP and 8 cP ($p < 0.001$ for all comparisons). For binder quantity, significant differences were observed between all binder quantity levels for change in length ($p < 0.001$), with length change decreasing as binder quantity increased. Change in diameter was significantly smaller for 30 g compared to 50 g ($p = 0.022$) and 70 g ($p < 0.001$). Relaxed density was significantly higher for 30 g compared to 50 g and 70 g ($p < 0.001$). Compressive strength showed significant differences between all levels ($p < 0.05$), decreasing as binder quantity increased. IRI was significantly higher for 70 g compared to 50 g ($p = 0.015$).

Table 10. Summary of the significant post-hoc comparisons of binder properties on dependent variables *Acacia mangium* briquettes

Dependent Variables	Binder Viscosity	Binder Quantity
Change in Length	14 cP ≠ 8 cP	30 g ≠ 50 g ≠ 70 g
Change in Diameter	14 cP ≠ 8 cP	30 g ≠ 50 g, 70 g
Relaxed Density	29 cP ≠ 14 cP, 8 cP	30 g ≠ 50 g, 70 g
CS in Cleft	29 cP ≠ 14 cP, 8 cP	30 g ≠ 50 g, 70 g
IRI	No Sig. differences	50 g ≠ 70 g

The higher viscosity binder (29 cP) produced briquettes with greater relaxed density and compressive strength. This suggests that a higher viscosity binder might be preferable for making briquettes with high durability. However, the compromise is that higher viscosity also leads to more significant changes in length and diameter, affecting the briquettes' dimensional stability. In contrast, briquettes made using lower viscosity binders (8 cP and 14 cP) recorded minor dimensional changes but with reduced mechanical strength. The quantity of binder used also has briquette properties. Increasing binder quantity generally led to decreased changes in length, lower relaxed density, and reduced compressive strength in the cleft while increasing changes in diameter. This suggests that there's an optimal binder quantity that balances dimensional stability with mechanical properties, which likely depends on the specific requirements of the end-use application. The observed interaction effects between binder viscosity and quantity for dimensional changes imply that the optimal binder quantity may differ depending on the viscosity used. For instance, a higher quantity might be necessary to achieve the desired mechanical properties when using a low-viscosity binder. In contrast, a lower quantity might suffice with a high-viscosity binder.

Conclusions

In conclusion, this study underscores the potential of utilizing Plantain peduncle and *Acacia. mangium* pods as effective biomass fuels in briquette production. The findings reveal that briquettes derived from Plantain peduncles demonstrate superior stability, density, and compressive strength compared to their *Acacia mangium* pod counterparts. Notably, the optimal binder combination (50 g and 29 cP) was identified, with increasing binder quantity contributing positively to briquette length stability, although no consistent trend was observed regarding diameter. In contrast, *Acacia mangium* pod briquettes showcased enhanced thermal efficiency, characterized by a higher gross calorific value, elevated volatile matter, and reduced ash content, emphasizing their efficiency as a fuel source. Both biomass materials exhibited low sulfur and nitrogen content, affirming their environmentally friendly attributes. The study highlights the importance of precisely balancing binder viscosity and quantity to optimize briquette characteristics. Future research avenues involve exploring the blending of these biomass types to enhance their strengths and mitigate weaknesses mutually. Additionally, investigating emissions during combustion and assessing alternative binder materials may improve briquette quality and performance. Overall, the research contributes valuable insights into sustainable biomass fuel development.

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