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Effect of Binder-Biomass Interaction on the Properties of Briquettes Produced from Bio-Wastes

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ABSTRACT

This research aimed to determine how increased binder level affects properties of briquettes produced from bio-wastes, while also promoting material valorizations and environmental remediation. The cassava and corn starch binders used for these experiments were prepared to form a slurry, and heated separately in a water bath until a gelatinous paste was formed. The carbonized peanut hull and corn cob char were measured and mixed thoroughly to form a composite. Cassava starch briquettes exhibited superior resistance to compression (6.94 MPa) compared to corn starch briquettes (3.08 MPa), confirming the structural benefits of the high binder content. Cassava starch briquettes exhibited greater density (710 kg/m^3), offering enhanced compaction and energy-per-volume advantages over corn starch briquettes (610 kg/m^3). Calorific values of 3545–3702 kcal/kg placed both fuels within standard-grade biomass specifications. Thermogravimetric analysis showed a stronger thermal stability and char-forming capability for cassava starch briquettes, with a final residue of 21.03% at 900°C versus 4.73% for corn starch. This research revealed the performance implications of using elevated natural binder concentrations in non-woody composite briquetting. It improves material valorization by converting low fixed-carbon agricultural wastes into efficient solid fuels. Furthermore, it supports environmental remediation and enhances pollution control through a clean-burning alternative.

Keywords: Biomass briquette, fossil fuel, natural binders, energy, corn cob, peanut hull, biomass wastes

INTRODUCTION

The survival of human activities, the development of the economy, society, and environment rely significantly on the availability of energy [1]. Fossil fuels, which have been the major source of energy, are non-renewable and associated with numerous challenges [2]. These challenges include greenhouse gas emissions, non-renewability, and rising fuel prices [3]. In recent times, the world has shifted to renewable energy sources that are biomass fuels to replace conventional fuel like coal, and petroleum. These biomass fuels are also known as green energy and include wood charcoal, agricultural waste, and animal dung [4].

A country such as Nigeria with significantly high population needs more energy than the conventional fuel can provide for her various activities. According to Garrido et al. [5], Nigeria is known to have massive biomass wastes in which 80% of these wastes can be processed to meet the energy demand of rural communities. These biomass waste remains a critical component of national energy mix for both developed and developing countries across the globe due to their potential of renewability. These potentials make them a viable alternative to fossil fuels (crude oil, natural gas, and coal) in achieving sustainable energy for heating applications, reducing environmental impact, creating bio-economies, and improving quality of rural and urban life [6]. Similarly, Olorunnisola et.al, [7] revealed how these agricultural residues are readily available in Nigeria, but they are mostly burned or dumped thereby polluting the environment. The team highlighted several economic benefits the country will derive if the wastes are transformed to bio or renewable energy to strengthen her energy mix.

Handling, transporting and storage of these biomass wastes in their raw form is usually a challenge due to their large volume and low bulk density [8]. Biomass briquetting, a densification technology, is one of the technologies used in overcoming this challenge and in improving the potential energy use of biomass, basically for household heating applications and power generation [9]. The densification technology is a process that involves compressing the biomass waste with or without a binding agent under relatively high temperature and pressure to achieve higher energy per volume of the material. This process increases the biomass properties such as bulk density and thermal properties. It also improves the handling, reduces the labor costs, and logistics [10] According to Kaliyan et.al [11] if densification is properly done it reduces the volume of agricultural residues by 8–10 times and increases the density to approximately 1000 to 1200 kg/m³. Dodyk Pranowo et al. [12], described a carbon briquette as a compressed solid fuel made from materials like biomass waste, coal dust, and other carbon-rich wastes that are often bound together using natural or synthetic binders. World energy council in 2016 revealed that biomass briquettes made from recycled waste will help reduce environmental issues, especially greenhouse gas emission buildup [13]. As a result, managing biomass waste in the design of biomass briquettes adds significantly to the sustainable and effective use of biomass wastes [14]. While the emissions from non-renewable fuels like coal are sequestered deep into the earth during the carboniferous period that of biomass was absorbed from the atmosphere. This exceptional quality and other potentials such as pollution reduction, ability to ignite easily, minimal smoke and odour have made the use of biomass briquettes in various applications, such as cooking, heating, and industrial operations attractive [15].

In addition, Ibitoye et al. [15] findings revealed that biomass contains natural binders or stabilizing agents, like lignin and proteins that are released and activated when it is densified at relatively high levels of temperature and pressure. To improve the essential properties such as cohesion, strength, fixed carbon, caloric value etc. of biomass briquettes it is necessary to apply binders during it production [16]. Meanwhile, Zhang et al. [17] emphasized the quality of the binding agent used as it affects the performance of briquettes. The team also identified algae with high protein and lignin content as a potential component which can act as binder while Waluyo et al. [18] revealed that adding algae as a binder enhanced the briquettes' density, energy value, and durability.

The briquette binders are mostly classified into organic, inorganic, and compound binders, according to their composition [17]. However, critical factors like availability, cost, properties of the raw material, densification pressure, low emissions, and the desired energy content of the briquettes. influence the choice of binders [19]. It is no doubt that when it comes to strong adhesion, good hydrophilicity and low cost, inorganic binders are suitable for biomass briquetting [20]. But these inorganic binders have lower combustion efficiency due to their limited calorific values, and the ash content is often high [21] unlike the organic binders that are readily available at lower price, with high heating value, and low ignition temperature [22].

Several researches have been carried out, ranging from exploring the effect of binders on biomass briquettes, to comparative study on the use of inorganic and organic binders, production of biomass briquettes from composite biomass wastes, and binder optimizations. Some of the researches include: The evaluation of binder effects on sawdust-based briquette for its suitability as a heating energy [23]; investigation of biomass briquettes made from maize cobs and

Ceiba pentandra at room temperature and low compacting pressure without the use of a binder [23]; and eevelopment and characterization of charcoal briquettes from water hyacinth [24,25]). In addition, Ibitoye et al., [15] investigated the combustion, physical, and mechanical characterization of composites biomass briquettes from carbonized banana stalk and corncob while Obi et al. [26] studied the characterization of biomass briquettes made from a blend of rice husk and palm oil mill sludge. Getu, et al. [27] worked on biomass briquette production from sugar cane bagasse and its potential as clean source of energy. These studies have shown promising results in different forms by positioning biomass briquettes as viable alternatives to fossil fuels in numerous applications like cooking and heating operations.

Nigeria is blessed abundantly with peanut hulls/husks and corn cobs which are mostly disposed by open burning, or landfill. The plan to work with a 1:1 mixture of peanut hull and corn cob biomass wastes is to investigate if the composite despite their low fixed carbon content will optimize performance in terms of improved densification, reduction in brittleness, and ash/volatiles control. The two natural binders were carefully selected because they are biodegradable, readily available local, renewable, and significantly cheap when compared to synthetic binders or imported adhesives. They are equally attractive for small-scale/low-cost briquette production. Also, the use of these different binders (cassava starch vs corn starch) offers the opportunity for a systematic comparison of binder type on densified composite briquette quality parameters such as mechanical strength, durability, calorific value, ash content, combustion behavior). No doubt this comparative investigation will identify optimum binder choice (locally available, cost effective) for feedstock blend. More so, the choice of 30%wt binder proportion for this research which is slightly higher; is to investigate the effect on mechanical strength, durability and handling, calorific value.

This research will help minimize waste, reduce dependency on non-renewable fuels and environmental disposal burdens. The successful production and characterization of these biomass briquettes to meet the standard thermal and combustion parameters will boost clean renewable energy supply. Furthermore, it will serve as a better alternative to traditional biomass (wood, charcoal) or fossil fuels in domestic or small industrial uses, thereby reducing dependency on non-renewable fuels.

However, to the best of our knowledge no research investigated or compared the effect of corn starch and cassava starch as natural binder on a composite biomass briquette made from corn cob and peanut hull. This research is timely as it will further strength the pathway to waste valorization by converting the disposal waste into a higher-value energy product.

MATERIALS AND METHODS

Materials

Carbonization furnace, drying oven, digital weighing balance, and a manual briquette machine were used to conduct the experiments. The two bio waste materials used for production of the biomass briquette are corn cob and peanut hull while cassava starch and corn starch served as the natural binders. The biomass wastes were locally sourced from the surrounding farms and bio waste facilities around Auchi in Edo State, Nigeria, where they were readily and significantly available.

(a)

(b)

Plate 1: (a) Corn cob/corn cob brittiques (b) peanut hull/peanut hull brittiques

Experimental Procedures

The biomass wastes were collected from the farms and bio facilities where they were discarded as residues. After collection, they were sorted to remove all the impurities, weighed and sun-dried for three days to lower the moisture content before carbonization. The dried corn cob and peanut hull (Plate 1) were separately fed into the furnace, with the lid properly closed to prevent oxygen from entering the combustion chamber while it burns to a temperature of 450°C for 40 minutes. The carbonizing process was followed by cooling before the biochar was removed and stored in a clean container with a lid to avoid contamination with impurities and ash buildup. The materials were then pulverized, weighed separately and stored in an airtight container for use.

Binder Preparation

The cassava and corn starch binder used for this experiment were prepared by dissolving 150 g each of cassava and corn powder into 200 ml of distilled water with a continuous stirring to form a slurry without any clogs or lumps. The two binder solutions were heated separately in a water bath at 100°C for 10 min with addition of 400 ml distilled to them while a continuous stirring was maintained until a gelatinous paste was formed.

Briquetting

The carbonized peanut hull and corn cob char were measured with a weighing balance in 1:1 and mixed thoroughly to form a composite. The resulting dry mixture was divided into two equal parts; each part was combined with the cassava and corn starch at 30% weight percentage ratios. The mixtures were stirred with a mechanical stirrer to achieve a uniform paste before filling into a manual briquetting machine made of cylindrical moulds with dimensions of 3 cm width and 6 cm height. The batch with cassava binder was compacted manually for 8 minutes to form the biomass briquettes. The wet biomass briquettes formed were weighed before sun drying them for 3 days to reduce the moisture content. The same procedure was repeated to produce the biomass briquette for the corn starch and after drying, each of the batches was packed in a well closed plastic container for characterization (Plate 2).

(a) (b)

Plate 2. (a) Corn starch briquettes (b) Cassava starch briquettes

Characterization

Density (bulk and unit density): Measured by weighing the briquette on a digital balance and measuring its volume using a Vernier caliper. It is calculated as the ratio of mass to volume.

Compressive Strength: Determined using a Universal Testing Machine. A load is applied gradually and continuously to the briquette until it fails/breaks. The maximum load at failure was recorded.

Drop/Shatter Strength (Durability): Evaluates resistance to handling. The briquettes were dropped from a specific height onto a concrete surface, and the weight of the broken pieces was measured to calculate the percentage of weight loss.

Proximate Analysis: This determines the composition of the briquette in terms of moisture, volatile matter, ash, and fixed carbon.

Moisture Content (MC): Determined by weighing the briquette and drying it in an oven at 110 °C for 24 hours until a constant weight was achieved. The percentage is calculated based on mass loss.

Volatile Matter (VM): The dried sample was placed in a covered crucible and heated in a muffle furnace at high temperature (e.g., 550 °C for 10 mins). The mass loss represents the volatile matter, excluding moisture.

Ash Content: The residue from the volatile matter test was heated without a lid in a muffle furnace at 550 °C for 1 h until constant weight, allowing the volatile compounds to burn off. The remaining residue was weighed and reported as ash.

Fixed Carbon (FC): Determined by subtracting the sum of the moisture, volatile matter, and ash percentages from 100%.

Thermal and Combustion Characteristics

Calorific value (Higher Heating Value - HHV): was measured using a bomb calorimeter. A known weight of the sample was ignited in an oxygen-pressurized bomb. The calorific value was calculated based on the temperature rise of the surrounding water and the calibration constant of the calorimeter.

Burning Rate/Time: A set amount of briquettes was ignited in a stove or furnace. The time taken to burn completely was recorded, or the mass loss over time was calculated.
Water Boiling Test (WBT): was measured as the cooking efficiency by placing a known amount of water in a pot on a stove fueled by the briquettes. The time taken to bring the water to boiling was recorded.

Thermogravimetric Analysis: The sample was heated in a controlled atmosphere within a TGA analyzer to measure weight loss as a function of temperature. This determines the thermal stability, degradation rates, and char residue of the briquettes

RESULTS AND DISCUSSION

Table 1 shows the physical thermal properties of the briquettes.

Table 1: Physical and thermal properties of corn cob/peanut hull briquettes

Binder Type	Burning Rate (g/min)	Compressive Strength (MPa)	Moisture Content (%)	Density(kg/m³)
Cassava Starch	0.24	6.94	13.3	710
Corn Starch	0.23	3.08	7.1	610

The burning rates of the cassava starch and corn starch-based briquettes at 0.23–0.24 g/min are quite close and very low. This is favorable when compared to a binder like clay [22]. A lower burning rate implies that the briquettes will have a longer fuel life per unit mass. The results also suggest that both binders offered efficient binding without significantly interfering with the combustion process. However, the 0.007 g/min difference between the two binders might be due to higher moisture content in cassava starch prompting it resistance to combustion though this is practically negligible as the results are safe and promising.

In addition, compressive strength is an essential mechanical property for briquettes as it determines the ability of briquettes to withstand applied loads without structural failure. The results from the compressive strength test for cassava starch at 6.94 MPa and corn starch at 3.08 MPa show that briquettes produced using the two binders are within plausible range as reported in the literature [22]. However, the better strength performance from the cassava starch compared to corn starch can be as result of its better gel formation properties upon activation, the rheological properties and a stronger intermolecular hydrogen bonding between starch molecules and biomass particles and a more effective particle interlocking.

The moisture content for the corn-starch biomass briquette at 7.1% is desirable and promising because it improves storage stability, mechanical durability and prevents energy wastage on evaporating water during combustion. Also, findings from Lewandowski, et al., [28] reveal that higher moisture content in cassava starch-bound briquettes can be attributed to the hygroscopic nature of cassava starch, which has a greater affinity for water molecules compared to corn starch. However, the 13.3% for cassava starch briquette is relatively high compared to the corn starch though still acceptable according to literature which suggest that moisture content for briquettes is in the range ~2.2% to ~15.9% depending on standard (e.g., ISO 17225)[29] for solid biomass fuels. This result further validates the lower burning rate for corn starch briquette compared to cassava starch briquette.

The density values of 710 kgm^{-3} for the cassava starch briquettes and the 610 kgm^{-3} for the corn starch briquettes show clear influence of binder chemistry on the compaction behavior during the briquetting process. The superior densification seen with cassava starch reflects its stronger gelatinization behavior and higher paste viscosity, which enhances inter-particle bonding and reduces void space during compression. This can be attributed to the superior binding properties of cassava starch, which facilitates better particle agglomeration and reduces porosity, [31]

The 610 kgm^{-3} for the corn starch briquette fall within this acceptable range for compressed and relaxed density values reported by Saleh and Yusha'u [30] despite the significant density difference between the corn starch and cassava-based briquettes. However, in comparison, cassava starch briquettes are likely to be preferred because higher density briquettes are generally demanded as they provide greater energy content per unit volume, require less storage space, and typically exhibit better combustion characteristics.

Table 2 presents the proximate analysis for corn cob/peanut hull briquettes.

Table 2: Proximate analysis for corn cob/peanut hull briquettes

Binder Type	Volatile matter (%)	Fixed carbon (%)	Ash content (%)
Cassava Starch	74.17	16.68	1.03
Corn Starch	73.00	18.25	1.33

The volatile matter of the cassava starch bonded briquette (74.17%) and that of corn starch bonded sample (73.00%) are relatively high which implies that a significant fraction of the biomass briquette are volatile gases and light organics that will ignite quickly during combustion and flame propagation. However, the volatile matter values are still within because the feedstocks for these briquettes are non-woody biomass-based which are known to have more hemicellulose and lower lignin. Comparing both samples, the corn starch briquettes demonstrate superior volatile matter characteristics with a 1.14% lower content than cassava starch briquettes. This difference, while seemingly small, can significantly impact combustion behavior, with corn starch briquettes offering more predictable and controlled burning characteristics suitable for sustained heating applications.

Conversely, the corn starch biomass briquette recorded a higher fixed carbon content (18.25%) compared to that of cassava starch (16.68%), suggesting that it would sustain a longer burning duration and a prolonged heat release. In addition, the fixed carbon content for both briquettes is low when compared to woody briquettes from coconut and sawdust. This is because of the combination of two biomass materials with relatively low carbon content.

The ash fractions (1.03% for cassava binder, 1.33% for corn starch binder) is an indication that peanut hull/corn cob combination with a 30% wt. binder concentration is excellent as the briquettes will produce a clean fuel in terms of ash generation. These results align with the required standards for good quality briquettes for non-wood residues which pegged the ash content below ~5% (or even ~4%). Lower ash is desirable because it minimizes clinker formation and enhances combustion efficiency. In terms of binder's effect, cassava starch briquettes demonstrate superior ash characteristics with significantly lower inorganic content. This makes it more suitable for heating systems where minimal ash production is critical.

Table 3 displays the calorific value and results of durability analysis for corn cob/peanut hull briquettes.

Table 3: Calorific value and durability analysis for corn cob/peanut hull briquettes

Binder Type	Calorific Value (Kcal/kg)	Durability (%)
Cassava Starch	3702	87.6
Corn Starch	3545	83.5

The calorific value of 3702 kcal/kg for cassava starch-bound briquettes ≈ 15.5 MJ/kg and that of corn starch-bound briquettes at 3545 kcal/kg ≈ 14.9 MJ/kg are slightly lower than the minimum 4000 kcal/kg for premium grade biomass briquettes according to ISO 17225-3. The two briquettes comfortably fit in the standard grade category because their values fall to within 3500-4000 kcal/kg. These calorific values are also promising especially that raw materials are readily available at no cost compared to traditional biomass (firewood, residues).

Comparatively, cassava starch briquettes have a higher calorific value compared to corn starch briquettes, with a 4.4% higher heating value (157 kcal/kg difference). This significant difference in energy content means that cassava starch briquettes would provide more efficient heating performance and better fuel economy in practical applications. Despite both samples falling short of premium grade ISO requirements, cassava starch briquettes demonstrate better energy characteristics and require less fuel mass to achieve equivalent heat output.

The 87.6% durability result for cassava starch-bound briquettes and 83.5% for the corn starch-bound briquettes shows that these briquettes will offer high resistance to breakage or degradation during handling, storage and transport. Although durability is often overlooked in research, these values indicate relatively robust briquettes. The values also demonstrate a justification to the choice of 30%wt. binder concentration for strong mechanical integrity which is key in non-woody biomass briquettes. The slightly higher durability for cassava binder shows that it produced a more mechanically sound briquette structure, this also validates the compressive strength results.

Table 4 and figures 1 and 2 show the result of TGA analysis of the briquettes.

Table 4: TGA Analysis for Corn Cob/Peanut Hull Briquettes

Temperature (°)	Corn Starch Sample	Cassava Starch Sample
200.00	75.99	75.98
250.00	76.03	76.49
300.00	76.24	76.38
350.00	76.01	76.51
400.00	70.86	75.78
450.00	73.61	77.20

500.00	70.83	77.24
550.00	70.89	72.06
600.00	61.48	66.24
650.00	33.68	54.70
700.00	24.15	28.36
750.00	24.13	26.17
800.00	24.60	81.72
850.00	24.76	18.69
900.00	4.73	21.03

TGA Plot for Corn starch Briquette

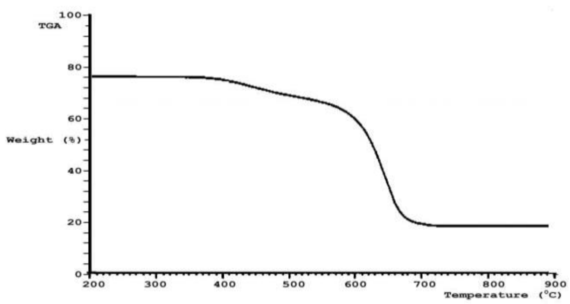

Figure 1: TGA Plot for Corn starch Briquette

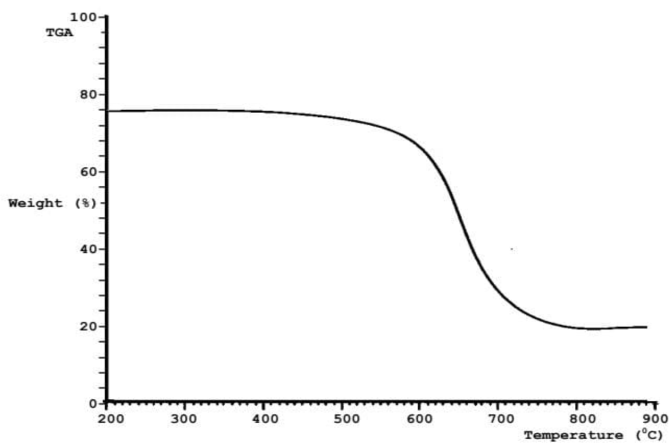

Figure 2: TGA for the peanut hull briquette

Thermogravimetric analysis is a critical analysis for briquettes as it helps to analyze the thermal degradation behavior with respect to binder composition thus providing insights into their thermal stability and decomposition patterns for potential application as natural binders in carbon briquette production from bio-waste. This analysis also helps to identify the distinct thermal decomposition stages of the starch materials, highlighting their stability characteristics and char formation potential under controlled heating conditions from 50 °C to 900 °C.

In this research, the biomass briquettes from both binders exhibit nearly identical behavior in the initial heating phase between 50-200°C**,** with corn starch showing 24.01% moisture loss and cassava starch showing 24.02% loss. This similarity aligns with Liu et al. [31] who reported 20-25% moisture loss for natural starches in this temperature range, indicating comparable hygroscopic properties regardless of botanical origin. The identical moisture content suggests similar storage conditions and inherent water-binding capacities, consistent with the amphiphilic nature of starch molecules containing both hydrophilic hydroxyl groups and hydrophobic glucose backbone structures. However, between 200-400°C the differences in thermal stability began to emerge as corn starch loses 5.13% of its mass while cassava starch loses only 0.20%. This shows that the cassava starch biomass briquettes still retain it exceptional resistance to thermal degradation. Also, this difference validates the finding of Chen et al., [32] that the dramatic difference between corn starch and cassava starch was attributed to the higher amylopectin content in cassava starch (75-85%) compared to corn starch (70-75%). An amylopectin with a well branched structure provides better thermal protection through stronger intermolecular hydrogen bonding networks. The impressive thermal resistance demonstrated by the cassava starch biomass briquettes between 200-400°C is very critical because it corresponds to the early stages of carbonization where maintaining structural integrity is essential for producing mechanically and thermally stable briquettes. It also validates that cassava starch had a better binding retention during the introduction. Furthermore, from the 400-600°C the biomass briquettes from the two natural binders experienced a significant mass loss but with markedly different patterns. The cassava starch biomass briquettes had a higher mass loss of 9.54% compared to that of corn starch at 9.38%. But the overall performance for the cassava starch biomass briquettes was better because it shows a more controlled degradation and higher retention. The most significant performance difference occurs during advanced carbonization, where cassava starch demonstrates superior char formation capabilities. At 650°C, cassava starch maintains 54.70% weight retention compared to corn starch's 33.68%, representing a 62% improvement. This enhanced char stability continues through to the final temperature, where cassava starch achieves 21.03% char yield compared to corn starch's 4.73%.

Also, the thermogravimetric analysis suggests different activation energies for thermal decomposition, with cassava starch requiring higher energy input for significant structural breakdown. This difference in activation energy, as reported by Lewandowski et al. [28], correlates with the observed thermal stability and explains the superior performance of cassava starch as a thermal binder.

In comparison to the literature [32], the biomass briquettes produced from the two natural binders show a promising thermal and mechanical integrity with the ones made from cassava starch more superior. For instance, the final residue for cassava starch at 21.03% significantly exceeds typical values of 5-15% reported for natural starches, Chen et al., [32], indicating exceptional carbonization potential. In terms of primary decomposition, briquettes made from corn starch shows rapid degradation at 300-400°C which is consistent with cereal starch behavior, while cassava starch maintains stability up to 400°C, exceeding literature expectations for root starches.

CONCLUSION

This research explored the production and characterization of composite briquettes produced from peanut hull and corn cob using 30% wt binder concentration of cassava starch and corn starch. This aimed to study the impact of increased binder proportions on mechanical strength, durability and handling, and the resulting energy characteristics of composite briquettes. Findings from this study show that this objective was successfully achieved, providing a deeper understanding of binder–biomass interactions at higher inclusion levels.

The briquettes demonstrated impressive burning behavior, which translated to slow fuel consumption and extended heat delivery especially for corn starch (0.23 g/min). However, the mechanical implications of the high binder level were more pronounced as the compressive strength values showed that cassava starch briquettes (6.94 MPa) benefited significantly from the increased binder ratio, achieving robust structural performance and surpassing corn starch briquettes (3.08 MPa). This confirms that the elevated binder concentration significantly improved mechanical strength and handling durability, especially for cassava-based briquettes.

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