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Influence of Compaction Parameters and Biomass Composition on Briquettes Produced from Cocoa and Kolanut Pod Residues

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Abstract

The sustainable utilization of agricultural residues for solid biofuel production offers a viable pathway for improving energy access and waste management in biomass-rich regions. This study investigates the influence of compaction parameters and biomass composition on briquettes produced from cocoa pod husks and kolanut pod husks using a locally fabricated briquetting machine. Briquettes were produced under varying mould heights, binder concentrations, biomass mixing ratios, and drying temperatures, and evaluated for bulk density, shatter index, fracture resistance, moisture content, and compressive strength. Results showed that compaction geometry and material composition significantly affected briquette quality, with bulk density ranging up to 0.006 g/cm³ and durability indices exceeding 90% under optimal conditions. A mould height of 4 mm, binder concentration of 5–10% starch, and balanced cocoa–kolanut pod ratios yielded the best combination of density and mechanical stability, while drying at 220°C enhanced moisture removal and strength development. Statistical analyses confirmed that mould height and biomass composition were the dominant factors influencing briquette performance, with drying temperature playing a key role in energy absorption and structural consolidation. The findings demonstrate that cocoa and kolanut pod residues can be effectively valorized into durable solid biofuels through optimized compaction and processing conditions, highlighting their potential for sustainable household and small-scale energy applications.

Keywords: Biomass Briquettes, Cocoa Pod Husk, Kolanut Pod Husk, Compaction Parameters, Briquetting Machine, Renewable Energy

Introduction

Agricultural production in Nigeria yields substantial quantities of biomass residues, many of which are underutilized despite their documented energy and economic potential (Jekayinfa *et al*., 2020) [10]. Among these residues, cocoa pod husks (CPH) and kolanut pod husks (KPH) are particularly abundant in the southwestern region, where large-scale cocoa and kolanut cultivation is concentrated. These residues possess favorable physicochemical characteristics—such as high lignocellulosic content, volatile matter, and natural binding properties—that make them promising feedstocks for solid biofuel production (Ofori & Akoto, 2020; Uchechukwu *et al*., 2018; Dinneya-Onuoha, 2025) [13, 17, 5]. Briquetting technology provides an effective means of transforming such loose biomass into dense, uniform, and energy-efficient solid fuels, thereby improving handling, combustion performance, and energy recovery (Marcus *et al*., 2022; Yirijor *et al*., 2022) [11, 18]. The conversion of CPH and KPH into briquettes represents a sustainable strategy for enhancing rural energy access, reducing dependence on firewood and charcoal, and supporting environmental conservation efforts in Nigeria (Jekayinfa *et al*., 2020; ECN, 2022) [10, 7].

Despite the availability and bioenergy potential of these residues, their use remains limited due to inadequate waste management systems, poor valorization practices, and the absence of affordable and locally designed conversion technologies. Cocoa pod husks alone constitute 70–80% of the dry weight of cocoa fruit, creating significant disposal challenges in cocoa-producing regions (Ouattara *et al*., 2021) [14]. Poor management often leads to open burning or uncontrolled decomposition, contributing to land degradation, greenhouse gas emissions, and the loss of valuable biomass resources (Ofori & Akoto, 2020; Marcus *et al*., 2022) [13, 11]. Although briquetting has been identified as a viable waste-to-energy solution, the technology remains underdeveloped in Nigeria due to high equipment costs, limited technical expertise, and lack of optimization for local biomass types such as cocoa and kolanut pod residues (Odogwu, 2025; ECN, 2022) [12, 7]. This underutilization perpetuates reliance on traditional fuels, exacerbates deforestation, and undermines energy security in rural communities.

The development of a locally fabricated briquetting machine tailored to the properties of CPH and KPH offers a pathway to address these challenges. Such innovation aligns with national renewable energy goals and supports rural economic empowerment through local machine fabrication and biomass-based enterprises (ECN, 2022; Yirijor *et al*., 2022) [7, 18]. Combining cocoa and kolanut pod residues in briquette production may further enhance briquette quality by leveraging the complementary characteristics of the two materials—cocoa pods providing high volatile matter for combustion efficiency and kolanut pods contributing improved structural integrity and binding performance (Asuquo *et al*., 2024) [3]. Harnessing this synergy can yield higher-quality briquettes suitable for household and small-scale industrial energy applications.

Accordingly, this study aims to design, fabricate, and evaluate a briquetting machine for converting cocoa and kolanut pod husks into solid biofuel briquettes using cassava starch as a binder. This research contributes to the advancement of sustainable energy solutions in Nigeria by promoting the circular use of agricultural residues, providing an alternative household fuel source, reducing dependence on non-renewable biomass, and mitigating environmental impacts associated with traditional fuelwood harvesting and waste mismanagement.

Materials and Methods

Study Site

The experiment was carried out in National Centre for Agricultural Mechanization, Idofian, Kwara State, Nigeria. NCAM, located in Northern Guinea savanna is situated in 8◦ 36N and 4◦69 E.

Materials for the Briquette Production

The materials used for the briquette production, Cocoa and Kolanut pod husks (Fig 1), are produced in large quantities in Nigeria’s southwestern agricultural regions (Dinneya-Onuoha, 2025) [5]. These residues possess favorable physicochemical properties suitable for briquetting—cocoa pod husks are rich in lignocellulosic components and exhibit high volatile matter, while kolanut pod husks offer good binding characteristics and moderate calorific value (Ofori and Akoto, 2020; Uchechukwu *et al*., 2018) [13, 17].

Sample Preparation Procedures

Cocoa and Kolanut pod husks used were sourced from Ifon, Osun State, Nigeria. The procured samples were milled using a hammer mill to reduce their size to below 4 mm for ease of compaction. The milled residues were then sieved using a set of standard sieves and a sieve shaker following the procedure of Dyjakon *et al*. (2020). Particles passing through the 4 mm sieves were collected as uniform fractions for the experiment. The starch binder at different levels of 5-25% was prepared with boiled water, stirred, and mixed at proportion of 50:50.

Fig1: a.) Cocoa Pod Husk and b.) Kolanut Pod Husk

Design of the Screw-Press Briquetting Machine

The screw-press briquetting machine was designed and fabricated to densify cocoa and kolanut pod husks, incorporating engineering analysis, material selection, and component development to ensure durability, high compression efficiency, and structural stability. The system consists of a hopper, a robust T-section mild steel main frame, and a 25-mm-thick cylindrical compression barrel, all dimensioned and analysed to withstand the expected compaction pressure delivered by a 3-tonne hydraulic jack. Fabrication involved cutting, welding, grinding, and assembling these components, including installing a threaded mount to secure the jack. In operation, milled biomass is manually fed into the cylinder, where the hydraulic jack drives a ramming piston to apply compressive force, resulting in compact, durable briquettes.

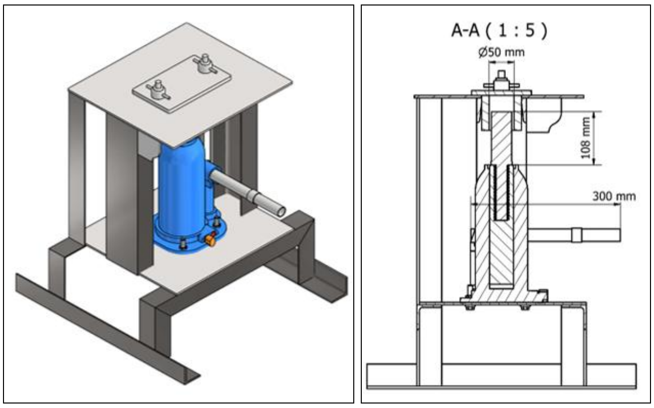

Fig 2: Isometric and Section view of the Briquetting machine

Briquette Production

The biomass mixtures were poured into moulds of 6, 4, and 2 mm and introduced into the cylinder of the briquetting press. Using the hydraulic jack incorporated with the press, the mixtures were compacted and allowed to rest for 120s. At the expiration of the holding time, the formed briquette were dried to constant mass in a hot-air oven set at 140°C, 160°C, 180°C, and 200°C with weights recorded at 30-minute intervals until no significant mass change was observed, ensuring effective drying without thermal degradation.

Determination of Physical and Mechanical Properties

Bulk density was determined following ASABE Standard S269.4 by measuring each briquette’s volume using caliperrecorded dimensions and its mass using a precision scale, after which density was calculated as mass divided by volume, Equ. (i). Durability was evaluated using an HV-2 Speed Adjusting Vibrator, where three briquettes per sample were weighed, vibrated for 5 minutes, reweighed, and their durability index computed, Equ. (ii). Impact resistance was assessed through a drop shatter test in which briquettes were dropped from 1.5 m three times, and percentage weight loss and shatter index were calculated using Equ. (iii). Compressive strength was measured using a Testometric Universal Testing Machine (100 kN BC), applying load at 10 mm/min until failure, and computed using Equ. (iv).

$$Bulk\ density\ \left(\frac{kg}{cm^3}\right) = \frac{weight\ of\ briquette}{density\ of\ briquette} \quad (1)$$

$$D = \frac{m_f}{mi} \times 100\% \quad (2)$$

$$\%\ weight\ loss\ = \frac{M_i - M_f}{Mi} \times 100\%$$

$$DI = 100 - \%\ weight\ loss \quad (3)$$

$$\sigma = \frac{F}{A} \quad (4)$$

Experimental Design and Statistical Analysis

A Box–Behnken Design (BBD) was employed to evaluate the effects of mould height, binder weight, CPH proportion, KPH proportion, and drying temperature on briquette quality. Binder content (5–25%) and CPH (40–80%) were primary mixture variables, while KPH (5–45%) served to improve structural properties. A simplex mixture plot (Fig 2) defines the design space. For mechanical properties, a Taguchi L_9 (3^4) orthogonal array was used to analyze the influence of mould height, binder mass, biomass composition, and drying temperature on compressive strength. Signal-to-noise ratios (nominal-is-best) and ANOVA were used to evaluate factor significance and model adequacy, while regression analysis provided predictive relationships.

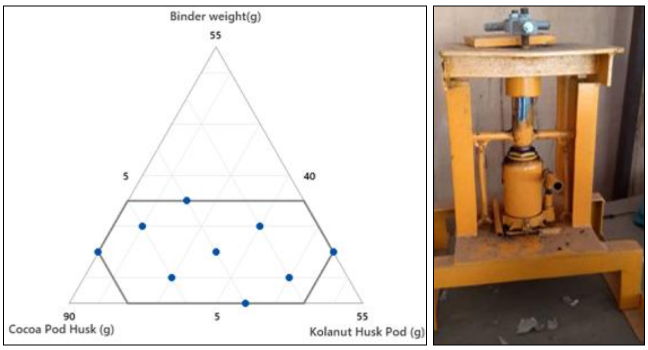

Fig 3: a) Simplex Design Plot of the Briquette Composition b) The Briquetting Machine

Results

Effects of Production Parameters on Briquette Properties

The physicochemical and mechanical test results are presented in Table 1,

Table 1: The Physicomechanical Performance of the Briquettes

		Bulk density (g/cm3)	Shatter Index (%)	Fracture Resistance (%)	Final weight (g)	Crushed Weight (g)
Mould	2.00	0.034	82.96	86.06	7.24	6.28
Height	4.00	0.048	89.33	88.65	11.50	10.21
(mm)	6.00	0.065	74.98	72.52	16.27	11.43
Binder	5.00	0.046	91.26	91.26	12.02	10.97
Weight	10.00	0.047	87.86	85.27	11.93	9.97
(g)	15.00	0.052	83.29	82.61	11.44	9.22
	20.00	0.049	72.40	75.71	11.64	8.15
	25.00	0.049	90.43	90.43	11.50	10.40
Cocoa-Kolanut (%)	60-25	0.05	80.84	79.89	11.09	8.52
	50-40	0.04	88.04	88.03	11.04	9.82
	50-30	0.05	78.44	78.37	10.05	7.32
	70-20	0.05	87.68	82.52	12.82	10.12
	70-10	0.05	66.36	73.05	13.23	8.98
	60-35	0.05	91.26	91.26	12.02	10.97
	60-15	0.05	90.43	90.43	11.50	10.40
	40-45	0.05	91.09	91.09	12.35	11.25
	80-5	0.05	87.74	87.74	12.23	10.73
Drying	140.00	0.040	87.15	82.41	10.12	8.34
Temp	160.00	0.053	75.85	76.56	13.42	9.68
	180.00	0.051	84.07	84.07	11.91	9.80
	200.00	0.043	84.41	84.42	10.15	8.43
	220.00	0.060	89.08	89.08	10.07	8.97

Mould Height

Mould height had a strong influence on briquette densification and mechanical performance. Bulk density increased progressively from 0.034 g/cm³ at 2 mm to 0.065 g/cm³ at 6 mm, reflecting greater material packing with increased compression height. However, mechanical durability did not follow the same pattern. The highest shatter index (89.33%) and fracture resistance (88.65%) were observed at 4 mm mould height, whereas 6 mm produced the weakest briquettes (shatter index: 74.98%; fracture resistance: 72.52%). Final and crushed weights also increased with height, indicating higher mass retention but reduced stability at excessive mould thickness. This aligns with findings by Dragusanu *et al*. (2022) [6] and Gong *et al*. (2015) [8], which highlighted the existence of optimal compaction parameters that maximize briquette integrity. Overall, a 4 mm mould height provided the best balance between compaction, density, and mechanical durability.

Binder Percentage

Binder weight showed a nonlinear effect on briquette quality. The highest mechanical durability occurred at 5 % of binder, where both shatter index and fracture resistance reached 91.26%. Increasing binder amount beyond 10 % reduced durability, with the lowest values recorded at 20 % (shatter index: 72.40%; fracture resistance: 75.71%). Although bulk density varied only slightly (0.046–0.052 g/cm³), higher binder levels generally reduced crushed weight, indicating reduced internal cohesion. The results suggest that 5–10 % binder produces the most structurally stable briquettes. This nonlinear behavior has been similarly reported by Ige *et al*. (2020) [9] and Sen *et al*. (2016) [16], who noted that starch binders perform optimally at moderate concentrations. The results indicate that 5–10% binder is sufficient to ensure strong interparticle bonding without compromising mechanical performance.

Drying Temperature

Drying temperature strongly influenced briquette density and mechanical performance. The highest bulk density (0.060 g/cm³) and high mechanical durability (shatter and fracture resistance: 89.08%) were observed at 220°C, confirming improved compaction and reduced internal moisture. Lower temperatures (140–160°C) produced weaker briquettes, with durability values as low as 75.85–82.41%, corresponding to higher crushed weight and final weight due to retained moisture. Temperatures between 180°C and 200°C provided moderate performance, indicating that high-temperature drying enhances structural stability and hardness.

Cocoa and Kolanut Pod Husk Composition

The briquette properties varied noticeably with changes in cocoa–kolanut pod composition. Bulk density ranged from 0.0438 to 0.0536 g/cm³, with the highest value observed at the 60–25% blend, indicating enhanced material packing at this ratio. Mechanical durability followed a similar trend, as the 60–35% and 40–45% blends produced the strongest briquettes, each recording a shatter index and fracture resistance of 91.26% and 91.09%, respectively. In contrast, the lowest mechanical performance occurred at the 70–10% blend, with a shatter index of 66.36% and fracture resistance of 73.05%, suggesting weaker cohesion at high cocoa and low kolanut proportions. Final weight and crushed weight generally increased with higher material loading, with the 40–45% and 70–20% blends yielding the heaviest briquettes (12.35 g and 12.82 g) and the greatest crushed weight (11.25 g and 10.12 g), indicating denser internal bonding. Overall, blends containing moderate proportions of kolanut pod (25–45%) and cocoa pod (40–60%) produced briquettes with superior density, durability, and resistance to mechanical degradation.

Moisture Content

Moisture content decreased steadily with increasing drying time (Fig 1), falling sharply from 64.56% at 1 hour to 27.18% at 2 hours and continuing to decline to 11.97% by the 4th hour. Beyond 5 hours, moisture loss slowed as the briquettes approached equilibrium, reaching very low levels of 3.89% and 1.61% at 6 and 7 hours, respectively. The distribution patterns indicated wider variability during early drying and more peaked, low-moisture distributions at later stages, confirming effective drying and attainment of near-constant mass toward the end of the process.

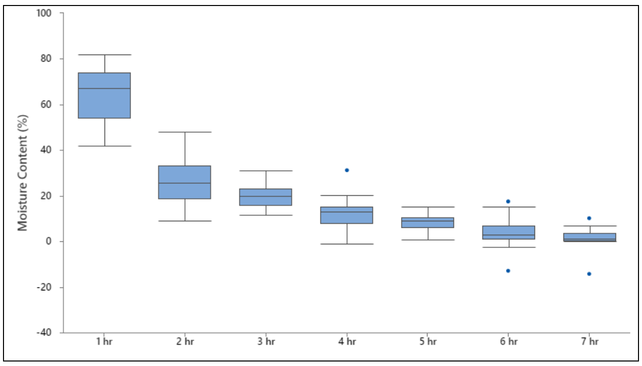

Fig 4: Distribution of Moisture Content vs Drying Time

Compressive Strength

The compressive test results showed low variability in Stress at Peak (StDev = 1.62 N/mm²) and Force at Peak (StDev = 51.0 N), indicating consistent strength across samples. Deflection at Peak and Strain at Peak displayed wider variation (StDev = 2.343 mm and 117.2%, respectively), while Energy to Peak showed moderate variability (StDev = 1.372 N·m). Taguchi analysis identified cocoa–kolanut pod composition as the dominant factor influencing all strength-related parameters, recording the highest signal-to-noise deltas for Stress at Peak (20.82), Force at Peak (20.77), Deflection (35.91), and Strain (35.84). Binder weight ranked second across most responses, while drying temperature consistently ranked third but produced the highest effect on Energy to Peak (S/N delta = 17.39). Mean force values ranged from 4997–5044 N across compositions, and mean energy-to-peak ranged from 11.51–12.56 N·m. Overall, the measured compressive properties varied systematically with the experimental factors, with cocoa–kolanut pod content exerting the strongest influence, followed by binder weight and drying temperature.

Table 2: Signal-to-noise (S/N) Ratio and Mean Response

Level	Signal to Noise Ratios			Means		
	Cocoa_Pod (g)	Drying Temp	Binder t(g)	Cocoa_Pod (g)	Drying Temp	Binder
Stress @ Peak (N/mm²)						
1	-5.287	-5.367	-5.327	1122	1118	1123
2	-5.258	-5.224	-5.213	1120	1123	1127
3	-5.275	-5.229	-5.28	1125	1126	1117
Delta	0.029	0.143	0.114	4	8	10
Rank	3	1	2	3	2	1
Def. @ Peak (mm)						
1	17.79	46.9	26.17	8.158	7.324	7.769
2	18.09	14.5	17.96	8.412	8.795	8.913
3	36.51	10.99	28.27	8.285	8.736	8.172
Delta	18.72	35.91	10.31	0.255	1.472	1.144
Rank	2	1	3	3	1	2
Force @ Peak (N)						
1	61.7	63.33	60.12	5022	5044	5049
2	46.97	52.99	49.86	5002	4997	5009
3	50.19	42.55	48.9	5030	5013	4997
Delta	14.73	20.77	11.22	27	47	52
Rank	2	1	3	3	2	1
Strain @ Peak (%)						
1	17.8	46.83	26.17	407.9	366.2	388.4
2	18.1	14.51	17.97	420.6	439.8	445.7
3	36.43	10.99	28.19	414.2	436.8	408.6
Delta	18.62	35.84	10.22	12.7	73.6	57.2
Rank	2	1	3	3	1	2
Energy to Peak (N·m)						
1	22.58	21	34.61	12.05	12.14	11.51
2	35.97	30.81	25.58	12.22	11.82	12.56
3	18.87	25.61	17.22	12.21	12.52	12.4
Delta	17.1	9.81	17.39	0.17	0.7	1.05
Rank	2	3	1	3	2	1

Discussions

The results demonstrate that mould height is a critical parameter governing briquette densification and mechanical performance. Bulk density increased with mould height, confirming improved particle packing at greater compaction depths; however, durability indicators peaked at an intermediate mould height of 4 mm. This highlights a trade-off between density and mechanical stability, where excessive mould height leads to uneven stress distribution and reduced heat transfer during compaction. Similar observations were reported by Dragusanu *et al.* (2022) [6] and Gong *et al.* (2015) [8], who showed that optimal compaction geometry promotes uniform pressure distribution and stronger briquettes. In contrast, Nurek *et al.* (2021) reported density reduction at higher mould heights due to pressure attenuation along the biomass column, a trend partially offset in this study by increased die-wall friction. Practically, the results confirm that moderate mould dimensions are essential for producing briquettes with adequate handling strength for storage and transport.

Binder percentage exhibited a pronounced nonlinear influence on briquette quality. Briquettes produced with low starch binder content (≈5%) achieved the highest shatter index and fracture resistance, indicating sufficient interparticle bonding without compromising the fibrous biomass matrix. Higher binder proportions reduced mechanical strength, likely due to increased organic dilution and reduced particle interlocking. This trend aligns with Ige *et al.* (2020) [9], who observed declining fixed carbon and durability at elevated binder contents, and with Sen *et al.* (2016) [16], who emphasized optimal rather than maximal starch addition. While Aransiola *et al.* (2019) [2] achieved improved durability at higher binder levels under elevated compaction pressures, the present results suggest that, for low-energy, manually operated systems, moderate binder content is more suitable. This has practical relevance for rural applications where binder availability and processing cost must be minimized.

Drying temperature strongly influenced moisture removal, density, and mechanical stability of the briquettes. Higher drying temperatures (≈220°C) produced denser and more durable briquettes due to enhanced moisture evaporation and effective starch gelatinization, consistent with Abdel Aal *et al.* (2023) [1]. Lower drying temperatures resulted in incomplete moisture removal, leading to weaker internal bonding and reduced strength. Moisture regression analysis further revealed that early-stage drying was controlled by mould thickness and composition, while later stages were governed by internal moisture diffusion, consistent with drying theory reported by Brishti *et al.* (2020) [4] and Paul and Martynenko (2022) [15]. These findings underscore the importance of controlled thermal treatment in ensuring dimensional stability, microbial resistance, and long-term storage performance of biomass briquettes.

Biomass composition emerged as the dominant factor influencing mechanical and compressive properties. Briquettes containing moderate cocoa–kolanut pod ratios consistently exhibited superior shatter resistance, fracture resistance, and compressive strength. Cocoa pod husk contributed lignin-rich fibrous structure for strength, while kolanut pod husk acted as a natural binder enhancing cohesion, confirming the complementary behavior reported by Ouattara *et al.* (2021) [14] and Onuegbu *et al.* (2021). Taguchi analysis further identified cocoa–kolanut composition as the most influential factor governing stress, strain, and deformation behavior, while drying temperature primarily controlled energy absorption. These results indicate that optimized blending of agricultural residues can reduce reliance on external binders and produce mechanically robust briquettes suitable for household and small-scale industrial energy applications.

Conclusions

This study demonstrated the successful fabrication and efficient operation of a briquetting machine capable of producing dense and durable briquettes from cocoa and kolanut pod residues. Optimal briquette performance was obtained at a composition of 30 g cocoa pod and 45 g kolanut pod, with 5–10% binder and a 4 mm mould height. Under these conditions, the highest bulk density (0.006 g/cm³), shatter index (91.3%), and fracture resistance (91.3 %) were achieved, particularly at a drying temperature of 220°C. Statistical analyses further confirmed that mould height, binder content, biomass ratio, and drying temperature exert significant influence on briquette density, durability, and overall mechanical strength.

Recommendations

It is recommended that a mould height of 4 mm and a starch binder concentration of 5–10% be adopted to achieve optimal briquette density, durability, and mechanical strength. Biomass blending ratios in the range of 30–50 g cocoa pod husk and 40–45 g kolanut pod husk are also recommended to enhance compaction efficiency and combustion performance. Further studies should focus on evaluating the combustion efficiency, emission characteristics, and environmental impacts of the produced briquettes in comparison with conventional solid fuels.

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