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Mechanical Properties of Carbonized Cashew Nut Shell–Sawdust Composite Briquettes under Different Drying Techniques

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ABSTRACT

The growing demand for sustainable energy has intensified interest in converting agricultural residues into high-quality biofuels. This study investigates the production and mechanical performance of composite briquettes made from cashew nut shells (CNS) and sawdust (SD) subjected to three drying methods: open sun drying, natural-convective solar drying, and forced-convective solar drying. CNS and SD were carbonized, milled, sieved into five particle sizes, and blended with cassava starch as a binder before compaction at 5 MPa. The effects of drying method, particle size, and biomass mixing ratio on moisture content and mechanical properties were evaluated. Results showed that forced-convective solar drying produced the lowest moisture content (3.96%) and the shortest drying time, while also yielding superior mechanical performance compared with the other methods. The highest compressive strength (0.53 MPa), density (563 kg/m³), and shatter resistance (98.77%) were obtained for briquettes composed of 50% CNS, 50% SD, and 0.2 mm particle size. Across all treatments, smaller particle sizes consistently improved density, compressive strength, and shatter resistance due to enhanced inter-particle bonding and reduced void spaces. Overall, forced-convective solar drying, combined with fine particle sizes and a balanced CNS–SD ratio, enhances the mechanical performance of composite briquettes from the agricultural residues.

INTRODUCTION

The increasing demand for sustainable and renewable energy has intensified research into alternative energy resources and the improvement of thermal-energy-utilizing systems over the past few decades (Gnanasekaran et al., 2023; Rijal et al., 2025). Environmental, economic, and social concerns have stimulated interest in the utilization of agricultural and forestry residues as renewable bioenergy feedstocks (Roder et al., 2022; Guo et al., 2024; Rijal et al., 2025). Biomass, including energy crops, agro-industrial residues, and forestry by-products, can be converted into energy-dense fuels that serve as viable alternatives to conventional fossil fuels (Tumpa et al., 2023; Guo et al., 2024). Among these resources, cashew nut shells (CNS), a by-product of the cashew processing industry, and sawdust (SD), generated from sawmills and wood-processing activities, are particularly abundant and often create environmental and waste management challenges when improperly disposed of (Cruz et al., 2024; Guo et al., 2024). The effective utilization of these residues can transform waste materials into value-added products such as biofuels, biomaterials, and bioenergy, thereby contributing to environmental sustainability and resource recovery

(Alizadeh et al., 2022; Zafeer & Bhat, 2023; Cruz et al., 2024; Guo et al., 2024; Gwoda et al., 2025; Neeraj et al., 2025).

One of the major drawbacks of raw biomass is its relatively high moisture content, which may exceed 50% depending on the biomass type and prevailing environmental conditions (Paul et al., 2019). Excessive moisture adversely affects combustion efficiency, reduces net energy density, increases transportation costs, complicates storage, and promotes biological degradation during storage (Chen, 2017). Biomass densification technologies, particularly briquetting, have been widely adopted to overcome these limitations by converting loose biomass into compact, uniform, and energy-dense solid fuels (Ishola et al., 2022). Briquetting improves fuel handling characteristics, increases bulk density, reduces storage volume, and enhances the calorific value of biomass fuels. In addition, briquettes provide a versatile and environmentally friendly energy source for domestic, commercial, and industrial applications, serving as sustainable alternatives to firewood and charcoal. The use of charred or carbonized biomass further improves fuel quality by reducing moisture and volatile matter contents while increasing fixed carbon content and combustion efficiency (Waheed et al., 2022; Kipngetich et al., 2023; Kabango et al., 2023; Osuolale et al., 2026).

When carbonized biomass is used for briquette production, binders such as starch are commonly added to improve particle adhesion and briquette integrity (Aransiola et al., 2019; Ishola et al., 2026). However, the addition of binders introduces moisture into the briquettes, making post-production drying an essential step. Adequate drying is necessary to minimize deterioration during handling, transportation, and storage while ensuring desirable mechanical and combustion properties. Drying is fundamentally a coupled heat and mass transfer process that plays a critical role in determining the quality, durability, and overall performance of briquettes.

Several drying techniques have been employed for biomass and briquette processing, including hot-air oven drying (Agbede et al., 2019a; Agbede et al., 2020a; Agbede et al., 2023a), microwave drying (Agbede et al., 2020a; Agbede et al., 2021; Agbede et al., 2023b), open sun drying (Agbede et al., 2020a; Agbede et al., 2020b; Ishola et al., 2026), natural-convective solar drying (Agbede et al., 2020a; Agbede et al., 2020b; Agbede et al., 2023c; Ishola et al., 2026), and forced-convective solar drying (Agbede et al., 2022; Oluremi et al., 2025; Ishola et al., 2026). Among these methods, open sun drying and solar drying technologies are particularly attractive because they utilize renewable solar energy and involve relatively low operating costs (Agbede et al., 2019b; Agbede et al., 2022). Nevertheless, open sun drying is highly dependent on weather conditions and is susceptible to contamination from dust, insects, rodents, and other environmental factors. Solar dryers, in contrast, provide a more controlled drying environment, protect products from contamination, and can significantly reduce drying time (Agbede et al., 2019b; Agbede et al., 2020a; Agbede et al., 2020b; Agbede et al., 2023c; Oluremi et al., 2025; Ishola et al., 2026). Both natural-convection (passive) and forced-convection (active) solar dryers utilize solar energy for moisture removal, although active systems employ forced airflow to enhance heat and mass transfer rates, thereby improving drying efficiency (Agbede et al., 2022; Oluremi et al., 2025; Ishola et al., 2026).

Previous studies have demonstrated the effectiveness of solar drying technologies for briquette production. Solar dryers have been reported to reduce drying time, improve moisture removal rates, enhance thermal efficiency, and improve product quality when compared with conventional open sun drying. Both natural and forced convective solar drying systems have shown considerable potential for improving the sustainability and efficiency of briquette processing (Molefe and Simate, 2019; Guibunda et al., 2024; Atienza et al., 2025; Gari et al., 2025; Ishola et al., 2026). These findings highlight the potential of solar drying systems as efficient and sustainable alternatives to conventional open sun drying methods in solid biofuel production.

Despite considerable advances in biomass densification and drying research, most existing studies have focused either on individual feedstocks or on drying methods without adequately examining the combined influence of drying conditions and feedstock characteristics on briquette quality. In particular, the interactive effects of drying method, biomass blending ratio, and particle size on the drying behavior and mechanical properties of composite briquettes remain insufficiently understood. Furthermore, limited information is available on the mechanical performance of composite briquettes produced from cashew nut shell and sawdust residues under different drying conditions.

Therefore, this study investigates the effects of open sun drying, natural-convective solar drying, and forced-convective solar drying on the drying characteristics and mechanical properties of CNS–SD composite briquettes. The influence of biomass blending ratio and particle size on briquette performance is also evaluated. It is hypothesized that forced-convective solar drying will produce briquettes with lower moisture content and superior mechanical properties, including compressive strength, shatter resistance, and durability, compared with open sun and natural-convective solar drying. It is further hypothesized that appropriate CNS–SD blending ratios and particle sizes will enhance particle bonding and structural integrity, resulting in improved briquette performance. The findings are expected to provide valuable insights into the selection of efficient drying strategies and suitable feedstock characteristics for the production of high-quality and sustainable solid biofuels.

MATERIALS AND METHODS

Collection and preparation of samples

Cashew nut shells (CNS) were obtained from Olam Edible Nut Industry in Afon, Asa Local Government Area (8.21667° N, 4.5669° E), Kwara State, Nigeria, while sawdust (African birch) was sourced from a sawmill in Ilorin (8.8525° N, 5.4044° E), Kwara State, Nigeria. Both biomass materials were sun-dried and manually sorted to remove impurities such as stones and dirt. The CNS were carbonized in a furnace at 250 °C for 3 h (Sarafa et al., 2022), while the sawdust was carbonized at 300 °C for 1 h (Putri et al., 2024). The resulting carbonized CNS and sawdust were then hammer-milled and sieved to obtain particle sizes of 0.2, 0.6, 1.0, 1.4, and 1.8 mm. The particle size range (0.2–1.8 mm) is consistent with values reported in the literature for briquette production (Faizal et al., 2015; Seboka et al., 2026). This range enables a systematic evaluation of the influence of particle size on the mechanical properties of the briquettes. Sieve analysis was conducted at the Department of Materials Science and Engineering, Kwara State University, Malete, Ilorin, Nigeria. The mixing ratios for the composite briquettes were generated using Design-Expert software.

Experimental design

In this study, experiments were designed using a D-optimal design within the Custom Design module of Design-Expert software (version 13). The minimum and maximum levels of the components, cashew nut shells (CNS) and sawdust (SD), as well as the particle size range, are presented in Table 1. Based on these constraints, a total of 20 experimental runs were generated using the D-optimal design and subsequently used for the production of CNS–SD composite briquettes. The selected ranges of cashew nut shells (50–70%) and sawdust (30–50%) were based on the complementary characteristics of the charred feedstocks, where CNS provides higher fixed carbon and energy density while sawdust contributes improved binding and structural integrity during densification (Mani et al., 2006; Kaliyan & Morey, 2009).

Table 1. Design Entries of Determining Factors for Briquettes Production Process

	Component	**Units**	**Minimum value**	**Maximum value**
	CNS	%	50	70
	Sawdust	%	30	50
Factor	Particle Size	mm	0.2	1.8

Briquette sample preparation and production

Briquettes were produced according to the experimental runs generated from the design of experiments. For each run, a measured proportion of charred CNS and SD particles was blended, and a starch-based binder was incorporated accordingly. The binder was prepared by dispersing 20 g of cassava starch in 40 cm³ of water, followed by gelatinization through the addition of 100 cm³ of boiling water at 100 °C to obtain a smooth, homogeneous starch gel (Oladosu et al., 2023). The starch concentration used in this study falls within the range reported in the literature to enhance the mechanical strength and durability of briquettes (Ajimotokan et al., 2019; Aransiola et al., 2019). Approximately 5 g of starch binder was added to 29 g of carbonized biomass mixture, corresponding to about 14.7% binder content on a mass basis for each briquette formulation. The prepared blend was then loaded into a mould, and briquettes were produced in triplicate for each experimental condition. Compaction was carried out at a pressure of 5 MPa with a dwell time of 5 min for all samples to minimize elastic recovery (spring-back) after compression. This process yielded cylindrical briquettes with a diameter of 50 mm and a height of 45 mm. Briquette fabrication was conducted at the Department of Mechanical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria. Replicate production was performed to ensure the reliability and reproducibility of the experimental results. The resulting carbonized CNS-SD briquettes are shown in Figure 2.

Drying of cashew nut shell–sawdust composite briquettes

Three batches of CNS–SD composite briquettes were prepared from the 20 experimental formulations generated by the design. One batch of briquettes was assigned to open sun drying, another to a natural-convection solar dryer, and the third to a forced-convection solar dryer. Drying experiments were conducted simultaneously using the three drying methods between 9:00 a.m. and 5:00 p.m. in December 2024. Briquettes that did not attain a constant mass by the end of a drying period were returned to their respective drying systems and subjected to further drying on subsequent days until a constant mass was achieved. Open sun drying was performed under prevailing ambient weather conditions. The natural-convection solar dryer operated through buoyancy-driven airflow, whereas the forced-convection solar dryer employed a blower to promote air movement through the drying chamber. Both solar dryers were locally constructed from galvanized steel sheets and fitted with transparent Pyrex glass covers. The glass cover permitted the transmission of solar radiation into the drying chamber, while the absorber surface was painted black to maximize solar heat absorption. The natural-convection and forced-convection dryers were fabricated with the same geometric dimensions, as illustrated in Figure 1a. The principal distinction between the two systems was the incorporation of a blower in the forced-convection unit to enhance air circulation. Schematic diagrams of the natural-convection and forced-convection solar dryers are presented in Figures 1b and 1c, respectively, while samples of the CNS–SD composite briquettes are shown in Figure 2. Throughout the drying process, the mass of each briquette was monitored at 60 min intervals using an OHAUS C-series digital balance with an accuracy of ±0.01 g. Measurements were continued until no further appreciable change in mass was observed. Ambient temperature as well as the internal temperatures of the solar dryers were also recorded during the experiments.

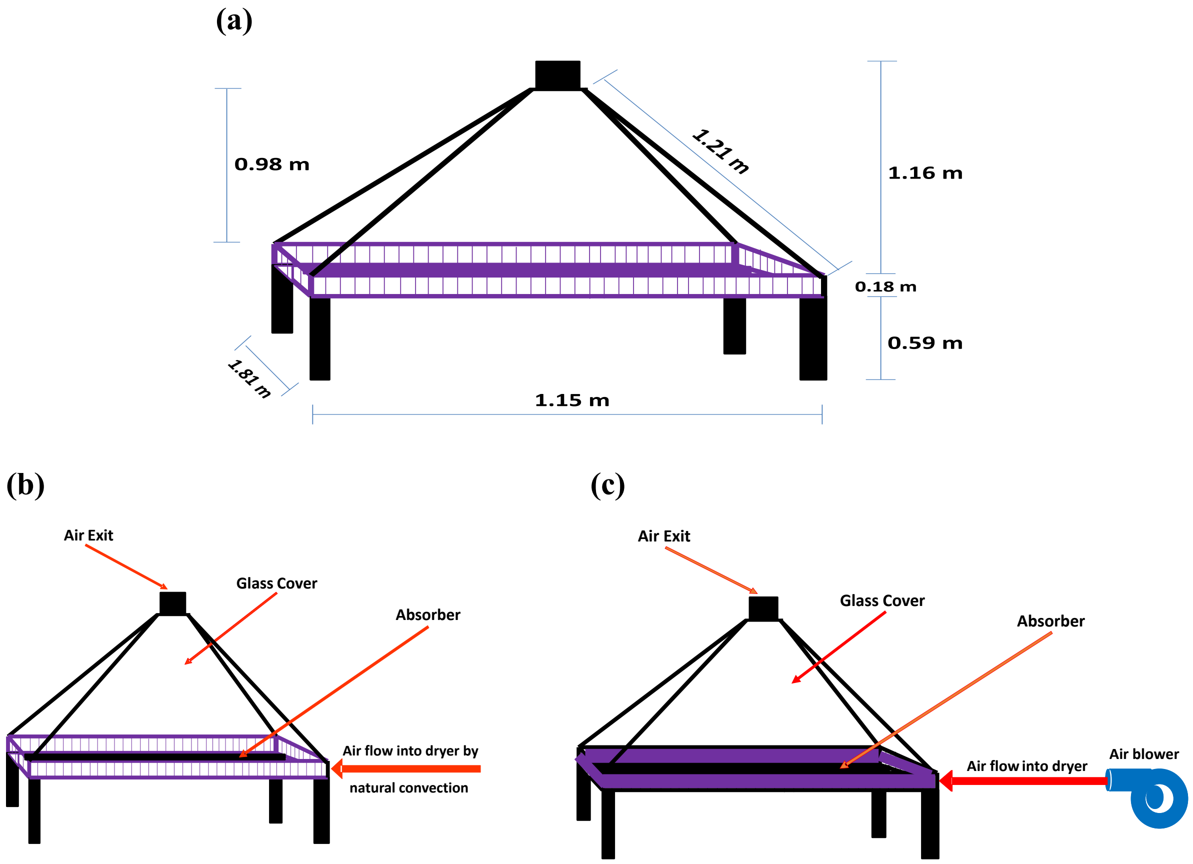

Figure 1: Schematics showing (a) dimensions of both dryers (b) natural-convection solar dryer (c) forced-convection solar dryer

Figure 2: Charred cashew nut shell-sawdust composite briquettes

Determination of moisture content

Moisture content was measured following ASTM D3173 (2013). Approximately 0.5 g of finely ground sample was placed in an oven and dried at 105 °C for 1 h. After drying, the sample was removed, cooled in a desiccator to prevent moisture absorption, and then reweighed (Ajimotokan et al., 2019). The moisture content on a wet basis was calculated using Equation (1):

$$M_c = \left(\frac{x_1 - x_2}{x_1}\right) x\ 100 \qquad (1)$$

where x_1 is the original mass of the sample, x_2 is the final (dried) mass of the sample, and M_c is the percentage of moisture content (wet basis).

Determination of Compressive Strength

Compressive strength is a key parameter for evaluating briquette durability, as it reflects the ability of briquettes to withstand handling, packing, and transportation without failure (Sarafa et al., 2022). The compressive strength of the carbonized biomass briquettes was determined using a modified unconfined compressive strength test based on ASTM D2166-85 (2008). Although originally developed for cohesive soils, this standard has been widely adapted in biomass briquette studies as a reproducible framework for assessing axial compressive performance under controlled loading conditions. The adaptation is justified by the similarity in test configuration, which involves uniaxial loading between parallel platens and measurement of failure under increasing compressive stress. In this study, the ASTM-based method was applied to carbonized biomass briquettes, which are heterogeneous, porous, carbon-rich composite materials produced through the thermochemical conversion of lignocellulosic feedstocks. Carbonization modifies the internal structure by decomposing volatile components and reducing polymeric binding phases, resulting in a predominantly brittle material whose mechanical behavior is governed by particle packing, residual char bonding, and binder effectiveness. Consequently, compressive testing in this context reflects mechanical integrity and fracture resistance rather than plastic deformation typical of uncarbonized biomass. The test was performed using an Instron Universal Testing Machine equipped with a 50 kN load cell. Each briquette was centrally positioned between two parallel loading plates, and compressive load was applied at a constant strain rate equivalent to 0.01667 N/mm²/s until catastrophic failure occurred. The maximum load at failure was recorded and used to calculate the compressive strength of the briquettes. This method provides a standardized basis for comparing the mechanical durability of carbonized briquettes under conditions relevant to handling, transportation, and storage (Oladosu et al., 2023; Mitchual et al., 2013; Ibitoye et al., 2024; Sánchez-Roque et al., 2025).

Determination of Briquette Density

Density is an important factor in assessing the handling and transportability of briquettes. The density of the briquettes was determined using the ASABE S269.4 method. The mass of each briquette was measured, and the volume was calculated by measuring its height and diameter with vernier calipers. Average measurements were taken for each briquette to improve accuracy (Nino et al., 2010). The density (ρ) was then calculated using Equation (2):

$$P_b = \frac{M_b}{V_b} \qquad (2)$$

where P_b is the density of the briquettes (kg/m^3), M_b is the mass of the briquettes (kg) and V_b is the volume of the briquettes (m^3).

Determination of Shatter Resistance

Shatter resistance is an important parameter for evaluating the durability of briquettes, particularly during handling, storage, stacking, and transportation. It provides an indication of the ability of briquettes to withstand impact loading without significant breakage. The shatter resistance of the briquettes was determined according to ASTM D440-86 (1998). Although this standard was originally developed for coal, it is also applicable to biomass briquettes because both materials possess similar characteristics, including a brittle agglomerated structure and susceptibility to impact-induced fragmentation during handling and transportation. The test procedure was modified to accommodate the geometry of the briquettes. Each briquette sample was dropped ten times from a height of 1 m onto a solid base. The mass retained after the drop tests was used as a measure of the briquette's resistance to breakage. The remaining portion was reweighed, and the shatter resistance (SR) was calculated using Equation (3):

$$SR\ (\%) = \frac{M_f}{M_0} \times 100 \qquad (3)$$

where M_0 is the initial mass of the briquette (g) and M_f is the final mass of the briquette after the drop tests (g)

RESULTS AND DISCUSSION

Production and drying of the composite briquettes

A total of 180 cylindrical CNS-SD composite briquettes were produced and dried using three methods: open sun, a natural-convection solar dryer, and a forced-convection solar dryer. Moisture removal occurred under all drying methods, as evidenced by the gradual reduction in briquette mass until a constant weight was attained for all samples. The drying times required to reach constant weight were 780 min (13 h) for open sun drying, 660 min (11 h) for the natural-convection solar dryer, and 480 min (8 h) for the forced-convection solar dryer. Peak drying temperatures were recorded between 300 and 600 min for all drying methods. The forced-convection solar dryer attained the highest temperature of 41.5 °C at 300 min, while the natural-convection solar dryer reached 39.9 °C at 540 min. Open sun drying recorded a maximum temperature of 39.3 °C at 600 min, as shown in Figure 3. The higher temperatures and enhanced airflow in the forced-convection solar dryer promoted greater moisture evaporation and accelerated drying, resulting in shorter drying times compared with open sun drying and natural-convection solar drying. This observation is consistent with the findings of Oluremi et al. (2025), who reported that drying cashew apple bagasse in a forced-convection solar dryer resulted in higher drying temperatures and shorter drying times than open sun drying.

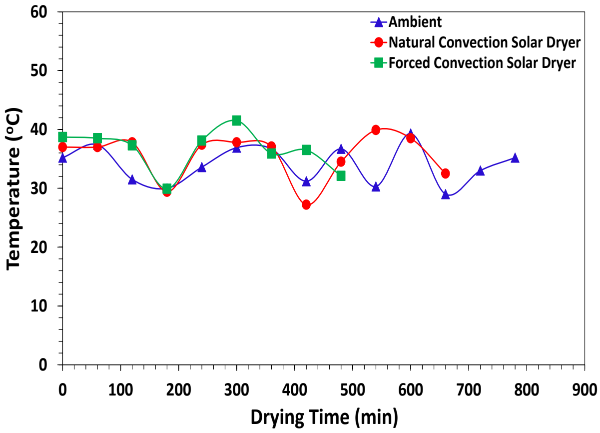

Figure 3: Plot of ambient, natural-convection solar dryer and forced-convection solar dryer temperatures versus drying time

Moisture content

The moisture contents of the composite briquettes produced under different drying methods, particle sizes, and CNS–SD blending ratios are presented in Table 2. Among the factors investigated, the drying method exerted the greatest influence on moisture content. Open sun drying produced the widest variation in moisture content (4.00–6.25%), reflecting the influence of fluctuating ambient conditions such as temperature, relative humidity, and wind speed. In contrast, both natural and forced convective solar drying yielded more uniform moisture contents, with most values clustering around 4.00%. The forced convective solar dryer achieved the lowest moisture content (3.96%), demonstrating superior moisture removal due to enhanced airflow and convective heat and mass transfer. Similar observations have been reported for solar drying systems, particularly forced-convection dryers, which achieve faster drying rates and lower final moisture contents than open sun drying (Rulazi et al., 2023; Gari et al., 2025).

Table 2: Moisture contents of the composite briquettes

Run	CNS (%)	SD (%)	Particle size (mm)	Open Sun Drying (%)	Natural Convective Solar Drying (%)	Forced Convective Solar Drying (%)
1	60	40	0.6	4.28±0.01	4.28±0.11	4.08±0.01
2	50	50	1.0	4.08±0.04	4.00±0.09	4.00±0.02
3	65	35	1.0	4.08±0.02	4.00±0.01	4.00±0.01
4	50	50	0.6	5.05±0.03	4.00±0.02	4.00±0.04
5	55	45	1.0	6.06±0.02	4.00±0.00	4.00±0.01
6	60	40	1.8	6.00±0.03	6.00±0.37	4.95±0.02
7	60	40	0.2	4.28±0.02	4.00±0.13	4.00±0.01
8	50	50	0.2	5.05±0.01	4.00±0.05	4.00±0.01
9	70	30	1.8	4.08±0.01	4.00±0.01	4.04±0.01
10	65	35	0.6	4.04±0.04	4.04±0.01	4.00±0.01
11	70	30	1.0	4.00±0.04	4.00±0.03	4.00±0.01
12	60	40	1.4	4.94±0.03	4.00±0.02	4.04±0.02
13	50	50	1.4	5.36±0.07	4.00±0.01	4.00±0.01
14	60	40	1.0	4.00±0.01	4.02±0.01	4.00±0.02
15	70	30	1.4	6.25±0.12	5.88±0.07	4.04±0.09
16	70	30	0.6	4.00±0.07	4.00±0.01	4.00±0.01
17	55	45	0.6	5.05±0.01	5.05±0.03	4.00±0.03
18	55	45	0.2	5.00±0.00	6.00±0.03	4.00±0.02
19	50	50	1.8	6.00±0.01	6.00±0.02	6.00±0.03
20	70	30	0.2	4.04±0.07	4.00±0.01	3.96±0.01

Particle size also influenced moisture removal, particularly under open sun and natural convective drying conditions. Briquettes produced with intermediate particle sizes (0.6–1.0 mm) generally exhibited the lowest and most stable moisture contents (≈4.00–4.28%), whereas both finer (0.2 mm) and coarser (1.4–1.8 mm) particles tended to retain more moisture. The higher moisture contents observed in coarse particles may be attributed to reduced surface area and greater internal diffusion resistance, while excessive fines may reduce pore connectivity and hinder moisture migration. Under forced convective drying, however, particle-size effects were considerably diminished, indicating that enhanced external heat and mass transfer reduced internal moisture transport limitations.

In comparison, the CNS–SD blending ratio had only a minor effect on moisture content. Although briquettes containing higher proportions of CNS (65–70%) generally exhibited slightly lower moisture contents than those containing higher proportions of sawdust, the differences were relatively small across the investigated range. Under both natural and forced convective solar drying, most CNS–SD formulations attained moisture contents close to 4.00%, indicating that moisture removal was governed primarily by the drying method and, to a lesser extent, particle size rather than biomass composition. Overall, the results demonstrate that drying method was the dominant factor affecting briquette moisture content, followed by particle size, while the influence of the CNS–SD blending ratio was comparatively limited.

Mechanical Properties of Composite Briquettes

Compressive Strength

The compressive strength of the cashew nut shell–sawdust composite briquettes under different drying methods is presented in Table 3.

Table 3: Compressive Strength of cashew nut shell-sawdust composite briquettes

Run	CNS	Sawdust	Particle size (mm)	Open Sun Drying (MPa)	Natural Convective Solar Drying (MPa)	Forced Convective Solar Drying (MPa)
1	60	40	0.6	0.10±0.02	0.11±0.01	0.13±0.01
2	50	50	1.0	0.21±0.02	0.28±0.01	0.30±0.02
3	65	35	1.0	0.15±0.03	0.14±0.02	0.14±0.02
4	50	50	0.6	0.22±0.02	0.45±0.02	0.47±0.02
5	**55**	**45**	**1.0**	0.18±0.02	0.18±0.02	**0.17**±0.01
6	60	40	1.8	0.04±0.01	0.08±0.01	0.03±0.01
7	60	40	0.2	0.29±0.01	0.20±0.01	0.37±0.01
8	**50**	**50**	**0.2**	**0.44**±0.01	**0.52**±0.02	**0.53**±0.01
9	70	30	1.8	0.08±0.06	0.09±0.03	0.08±0.03
10	65	35	0.6	0.12±0.02	0.13±0.02	0.15±0.02
11	70	30	1.0	0.12±0.02	0.09±0.02	0.14±0.01
12	60	40	1.4	0.04±0.02	0.09±0.02	0.05±0.02
13	50	50	1.4	0.14±0.03	0.20±0.02	0.20±0.02
14	60	40	1.0	0.07±0.02	0.09±0.02	0.10±0.02
15	70	30	1.4	0.08±0.02	0.09±0.02	0.09±0.01
16	70	30	0.6	0.32±0.03	0.34±0.03	0.37±0.03
17	55	45	0.6	0.19±0.02	0.20±0.02	0.20±0.02
18	55	45	0.2	0.20±0.02	0.19±0.02	0.21±0.01
19	50	50	1.8	0.14±0.02	0.16±0.02	0.18±0.02
20	70	30	0.2	**0.22±0.02**	0.30±0.01	**0.32**±0.02

The results show that compressive strength varied significantly with particle size, biomass mixing ratio, and drying method. Among all experimental runs, briquettes produced in Run 8 (50% CNS, 50% SD, and 0.2 mm particle size) exhibited the highest compressive strength values of 0.44, 0.52, and 0.53 MPa for open sun, natural convective solar drying, and forced convective solar drying, respectively. Conversely, briquettes produced in Run 6 (60% CNS, 40% SD, and 1.8 mm particle size) recorded the lowest compressive strength values of 0.04 MPa under open sun drying and 0.08 MPa under both natural and forced convective solar drying. The results indicate a clear inverse relationship between particle size and compressive strength, where briquettes produced from smaller particle sizes demonstrated higher compressive strength, while those produced from larger particle sizes showed reduced strength. This trend has been widely reported in the literature (Mani et al., 2006; Kaliyan & Morey, 2009; Pang et al., 2019; Nuryawan et al., 2025). Abineno et al. (2025) attributed this behavior to enhanced inter-particle bonding in smaller particles due to increased surface area, which promotes stronger adhesion and mechanical interlocking. In contrast, larger particle sizes possess lower surface contact, resulting in weaker bonding and reduced compressive strength.

In addition, briquettes dried by forced convective solar drying consistently exhibited higher compressive strength compared to those dried under open sun and natural convective solar drying. The maximum compressive strength of 0.53 MPa recorded under forced convective drying can be attributed to higher and more uniform drying temperatures, improved airflow, shorter drying duration, and more effective moisture removal. These factors contribute to increased structural integrity and mechanical stability of the briquettes, consistent with findings reported by Rulazi et al. (2023).

Density of the Composite Briquettes

The densities of the cashew nut shell–sawdust composite briquettes dried in open sun, natural-convection solar dryer, and forced-convection solar dryer are presented in Table 4.

Table 4: Density of the composite briquettes

Run	CNS (%)	SD (%)	Particle size (mm)	Open Sun Drying (kg/m^3)	Natural Convective Solar Drying (kg/m^3)	Forced Convective Solar Drying (kg/m^3)
1	60	40	0.6	329.12	334.21	366.25
2	50	50	1.0	366.14	372.34	421.61
3	65	35	1.0	313.58	313.78	322.26
4	50	50	0.6	409.61	421.90	454.52
5	55	45	1.0	243.03	256.42	308.53
6	60	40	1.8	299.41	303.23	336.30
7	60	40	0.2	382.19	400.28	443.78
8	**50**	**50**	**0.2**	**496.59**	**499.42**	**563.22**
9	70	30	1.8	171.10	203.64	336.62
10	65	35	0.6	360.07	360.17	331.19
11	70	30	1.0	311.25	368.63	400.96
12	60	40	1.4	322.26	333.23	356.16
13	50	50	1.4	311.16	387.12	401.94
14	60	40	1.0	323.44	324.64	365.10
15	70	30	1.4	299.99	301.33	323.54
16	70	30	0.6	358.28	356.23	358.56
17	55	45	0.6	332.23	342.11	367.42
18	55	45	0.2	418.53	487.03	507.17
19	50	50	1.8	303.62	320.29	353.14
20	70	30	0.2	353.64	353.97	391.11

The results indicate that briquette density varied with particle size, biomass composition, and drying method. Among all experimental runs, Run 8 (50% CNS, 50% SD, and 0.2 mm particle size) exhibited the highest density values of 496.59, 499.42, and 563.22 kg/m³ for open sun, natural convective solar drying, and forced convective solar drying, respectively.

The results clearly show that briquette density is inversely proportional to particle size, such that smaller particle sizes produced higher-density briquettes. This behavior can be attributed to improved inter-particle bonding and increased contact surface area associated with finer particles, which enhances compaction and reduces pore spaces within the briquette structure (Gebrehiwet et al., 2025). As the particle size of CNS and SD decreases, greater packing efficiency is achieved, resulting in fewer void spaces and higher briquette density (Setter et al., 2021).

It was also observed that briquettes dried using forced convective solar drying consistently exhibited higher densities than those dried under open-sun conditions. This can be attributed to more effective moisture removal, higher drying temperatures, and uniform airflow within the forced-convection solar dryer, which promote stronger bonding and improved structural consolidation of the briquettes. The observed variation in density follows a similar trend to that of compressive strength across all drying methods.

The strong correlation between briquette density and compressive strength observed in this study agrees with previous reports, which indicate that briquettes with higher density generally exhibit higher compressive strength (Mitchual et al., 2013; Nuryawan et al., 2025). High-density briquettes possess fewer void spaces, leading to reduced compressibility and improved resistance to mechanical failure. In contrast, low-density briquettes contain more void spaces, which can act as stress concentration points and promote cracking or breakage when subjected to applied loads (Bello & Onilude, 2020).

Shatter Resistance

Table 6 presents the shatter resistance of composite briquettes dried under open sun, natural convective solar drying, and forced convective solar drying conditions. The highest shatter resistance values of 94.45%, 95.35%, and 98.77% were obtained for open sun, natural-convection, and forced-convection solar drying, respectively, at Run 8 (50% CNS, 50% SD, particle size of 0.2 mm). In contrast, the lowest shatter resistance values of 31.32 %, 32.67 %, and 49.54% were recorded at Run 9 (70% CNS, 30% SD, particle size of 1.8 mm) for the respective drying methods.

The results indicate that shatter resistance is inversely proportional to particle size, with finer particles producing briquettes with greater resistance to breakage. This trend can be attributed to enhanced inter-particle bonding and reduced pore spaces associated with smaller particle sizes (Setter et al., 2021; Abineno et al., 2025). A similar increase in shatter resistance with decreasing particle size has been reported in the literature (Mekonen *et al.*, 2024).

It was also observed that shatter resistance followed a trend similar to that of density and compressive strength across all drying methods. This behavior is expected, as strong correlations exist among these mechanical properties. Briquettes with higher density and compressive strength generally exhibit improved resistance to impact and handling stresses. Comparable relationships between shatter resistance, density, and compressive strength have been reported by Tuates Jr. *et al.* (2020) and Alhaji *et al.* (2025). Furthermore, briquettes dried using the forced-convection solar dryer consistently exhibited higher shatter resistance than those dried under open sun and natural convective conditions. This can be attributed to more effective moisture removal, uniform drying, and improved structural integrity achieved under forced convective drying. The maximum shatter resistance obtained in this study (98.77%) is slightly higher than the value of approximately 98 % reported by Ajiboye et al. (2016) for sawdust charcoal briquettes produced at a 50:50 mixing ratio and a particle size of 0.2 mm, representing an improvement of about 0.77 %.

Table 6. Shatter resistance of the composite briquettes (%)

Run	CNS (%)	SD (%)	Particle size (mm)	Open Sun Drying	Natural Convective Solar Drying	Forced Convective Solar Drying
1	60	40	0.6	**63.60**	83.36	**94.47**
2	50	50	1.0	82.57	77.96	85.84
3	65	35	1.0	72.03	87.54	91.42
4	50	50	0.6	83.43	85.11	94.98
5	55	45	1.0	**70.47**	86.85	91.69
6	60	40	1.8	**48.48**	58.43	**76.51**
7	60	40	0.2	71.97	**91.18**	97.57
8	**50**	**50**	**0.2**	**94.45**	**95.35**	**98.77**
9	70	30	1.8	**31.32**	**32.67**	49.54
10	65	35	0.6	72.56	89.76	95.20
11	70	30	1.0	69.46	89.58	90.62
12	60	40	1.4	61.22	67.69	87.21
13	50	50	1.4	66.55	77.54	91.05
14	**60**	**40**	**1.0**	**63.04**	**82.32**	**93.35**
15	70	30	1.4	31.41	33.02	**55.72**
16	70	30	0.6	85.16	**92.61**	93.12
17	55	45	0.6	81.29	88.41	92.53
18	55	45	0.2	**83.35**	**92.07**	**95.65**
19	50	50	1.8	34.37	55.64	83.98
20	70	30	0.2	90.34	92.05	96.04

CONCLUSION

This study demonstrated that both drying method and particle size significantly influence the mechanical properties of cashew nut shell–sawdust composite briquettes. Among the drying techniques, forced convective solar drying outperformed natural convective and open sun drying by achieving the shortest drying time, the lowest final moisture content (3.96%), and superior briquette quality, including the highest compressive strength (0.53 MPa), density (563 kg/m³), and shatter resistance (98.77%). Across all drying methods, the best mechanical properties were consistently observed at a composition of 50% CNS, 50% sawdust, and a particle size of 0.2 mm. Overall, the results indicate that the combination of controlled solar drying, particularly forced convective solar drying, with appropriate particle size and biomass blending ratio produces high-quality, durable solid biofuels from cashew nut shell and sawdust residues. This approach offers an environmentally sustainable pathway for agricultural waste valorization and contributes to the development of alternative renewable energy resources.

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