



# Drying Kinetics and Combustion Characteristics of Carbonized Cashew Nut Shell Briquettes Under Open Sun, Passive and Active Solar Drying

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## Abstract

*This study investigated the influence of different drying methods (open sun, passive solar, and active solar drying) on the drying kinetics and combustion properties of carbonized cashew nut shell briquettes (CCNS-B). Cashew nut shells were carbonized at 250 °C for 3 h, pulverized, and densified using cassava starch as a binder at a pressure of 5 MPa. The briquettes were then subjected to controlled drying conditions, and their drying behaviour was evaluated using moisture ratio, drying rate, and effective moisture diffusivity. In addition, thin-layer drying models were applied to describe the drying kinetics, while proximate and ultimate analyses were used to assess fuel quality. The results showed that active solar drying achieved the shortest drying time (900 min) compared to passive solar (1080 min) and open sun drying (1260 min). Drying occurred entirely in the falling-rate period, indicating diffusion-controlled moisture transport. Effective moisture diffusivity increased from  $4.50 \times 10^{-9} \text{ m}^2/\text{s}$  (open sun) to  $9.49 \times 10^{-9} \text{ m}^2/\text{s}$  (active solar). Among twelve evaluated thin-layer models, the Midilli-Kucuk model best described the open sun and active solar drying, while the logarithmic model best depicted the kinetics of the passive solar drying of the briquettes ( $R^2 \geq 0.990$ ). Proximate analysis revealed improved fuel quality under active solar drying, with lower moisture (2.01%), reduced volatile matter (51.04%), and higher fixed carbon (38.62%). Ultimate analysis showed minimal variation in elemental composition across drying methods. The higher heating value ranged from 25.18 to 25.76 MJ/kg, with the highest value observed in active solar drying. Overall, active solar drying produced superior briquette quality and is recommended for efficient biomass fuel processing.*

**Keywords:** Biomass fuel, briquettes, cashew nut shell, effective moisture diffusivity, solar drying.

## 1.0 Introduction

The increasing demand for sustainable energy has driven extensive research into alternative energy sources and the improvement of thermal energy systems over the past few decades [1], [2]. Sustainability concerns have further stimulated the exploration of agricultural and forestry residues as potential bioenergy feedstocks [2], [3], [4]. Biomass is recognized as one of the most important energy sources and ranks as the fourth largest energy source globally, particularly in developing countries [5], [6]. Biomass wastes include cashew nut shells, sugarcane bagasse, sawdust, municipal waste, waste paper, rice husks, straw, cornstalks, walnut shells, and wood pellets [7]. These wastes can be densified into solid fuels, providing a viable alternative to conventional fossil fuels [4], [8].

Cashew (*Anacardium occidentale* L.) is one of the major cash crops in Africa and ranks among the leading edible nuts globally [9]. Nigeria is one of the largest producers of cashew nuts in Africa and ranks among the top producers worldwide, with an annual production capacity of about 240,000 tonnes and yields ranging from 300 to 800 kg/ha [10]. Valuable products are obtained from both the nut and the apple, including cashew nut shell liquid, juice, jam, and alcohol [11]. Effective utilization of cashew nut processing residue can convert waste into valuable energy resources [4], [12], [13], [14], [15].

A major limitation of raw biomass is its high moisture content, which can exceed 50% depending on the species and environmental conditions [16]. High moisture content reduces energy density, lowers combustion efficiency, and increases transportation costs [17]. To address these challenges, biomass briquetting has emerged as an effective solution, converting loose biomass into dense, uniform solid fuels with improved calorific value and reduced moisture content compared to raw biomass [5, 18]. Briquettes can be used for household cooking, small-scale industrial heating, and large-scale power generation. In addition, briquettes help reduce deforestation by serving as a substitute for firewood and charcoal [19]. The use of carbonized biomass further enhances fuel quality by reducing moisture and volatile matter while increasing fixed carbon and heating value, thereby improving combustion characteristics [20], [21], [22].

Despite these advantages, a major limitation of biomass briquettes is moisture retention after production, which affects storage, handling, and transportation. Open sun drying is widely used due to its low cost; however, it requires large space and depends heavily on weather conditions [23]. Uncontrolled parameters such as ambient temperature, relative humidity, and wind speed make open sun drying inefficient in terms of moisture removal rate, drying time, and final product quality [6]. In addition, prolonged exposure during open drying increases the risk of contamination by dust, insects, and other impurities [24]. Alternative drying methods, including solar drying, hot air oven drying, microwave drying, and hybrid systems, have been explored for biomass drying [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35].

Solar dryers offer a cost-effective and energy-efficient alternative to hot air oven, microwave, open sun, and hybrid drying methods by utilizing renewable solar energy to achieve controlled drying conditions, reduced operating costs, improved product quality, and lower environmental impact, while avoiding the high energy consumption of ovens and microwaves and the poor controllability and contamination risks associated with open sun drying [25], [29], [32], [36], [37]. Solar drying systems are commonly classified into passive and active types based on the mode of air circulation, although other classifications such as direct, indirect, mixed-mode, and hybrid systems also exist depending on design and heat transfer configuration [36], [37]. Passive solar dryers operate using natural air movement without external power, making them simple, low-cost, and energy-independent, but typically slower and more dependent on weather conditions. In contrast, active solar dryers use forced convection via fans or blowers powered by electricity or solar energy to control airflow, resulting in faster, more uniform drying, though at higher cost and energy demand [36], [37].

Solar energy-based drying systems provide a sustainable alternative to conventional drying technologies such as hot air ovens, microwave dryers, open sun drying, and hybrid systems. They harness renewable energy to maintain relatively controlled drying environments, thereby reducing operating costs, improving product quality, and minimizing environmental impacts. Unlike hot air and microwave systems, which require substantial external energy input, and open sun drying, which suffers from poor process control and contamination risks, solar dryers present a more balanced and sustainable option for biomass drying applications [25], [29], [32], [36], [37]. Depending on their configuration, solar dryers are generally categorized into passive and active systems based on airflow mechanism, although broader classifications such as direct, indirect, mixed-mode, and hybrid designs also exist depending on heat transfer arrangement and system architecture [36], [37]. In passive systems, air movement occurs naturally through buoyancy-driven convection without external mechanical assistance, making them simple, inexpensive, and energy-autonomous, but relatively slow and highly dependent on climatic conditions. Active solar dryers, on the other hand, rely on forced convection using electrically or solar-powered fans to regulate airflow, which improves drying uniformity, enhances moisture removal rate, and shortens drying time, albeit with higher energy and equipment requirements [36], [37].

Empirical studies have demonstrated the effectiveness of solar-assisted drying systems for briquette processing. Gari *et al.* [6] evaluated an active-mode double air-pass solar tunnel dryer for charcoal briquettes and reported a moisture reduction from 45.31% to below 10% within 5–6 hours, whereas open sun drying required 14–16 hours to achieve comparable levels. Similarly, Molefe and Simate [38] investigated thin-layer drying behavior of poultry litter briquettes under open sun and solar tunnel drying conditions, observing moisture reduction from 61% to between 0.2% and 11.2% over 31–55 hours, with the solar dryer performing significantly faster; their results further indicated that the logarithmic model best described the drying kinetics. Using a computational fluid dynamics approach, Guibunda *et al.* [39] analyzed a solar tunnel dryer for charcoal briquettes under Mozambican climatic conditions and reported operating temperatures between 36.5 °C and 65 °C, air velocities up to 33.5 m/s, and a mass flow rate of 1.36 kg/s, achieving moisture reduction from 50% to 10% and confirming improved drying efficiency and sustainability performance. In another study, Atienza *et al.* [40] examined a passive indirect solar dryer equipped with perforated baffles and thermal energy storage for coconut briquettes and found that the modifications enhanced heat utilization, improved product quality, and reduced drying time to about one-third of that required for traditional sun drying. Collectively, these findings demonstrate the strong potential of solar drying systems to improve drying performance and product quality in briquette production.

Although solar drying of biomass briquettes has been reported in a small number of studies, the existing literature remains limited in scope and does not adequately address the drying behavior of different briquette systems under solar-assisted conditions. More importantly, to the best of the authors' knowledge, no study has specifically investigated the solar drying of carbonized cashew nut shell briquettes, particularly with respect to their drying kinetics, moisture transport mechanisms, and the influence of drying method on final fuel quality. This reveals a clear and significant research gap, as carbonized cashew nut shell briquettes represent a high-potential biofuel whose drying behavior is critical to optimizing storage stability and combustion performance. Addressing this gap is therefore essential for advancing efficient solar drying strategies and improving the overall quality and applicability of biomass-derived solid fuels.

## 2.0 Materials and Methods

### 2.1 Collection and preparation of materials

Cashew nut shells (CNS) were supplied by Olam Edible Nut Industry, located in Afon, Asa Local Government Area (8.21667° N, 4.5669° E), Kwara State, Nigeria; therefore, manual shell removal from the nuts was not required. The biomass was sorted to remove unwanted particles and subsequently sun-dried to reduce the moisture content to approximately 10% (wet basis), as recommended by Pandey and Dhakal [41] and Sarafa *et al.* [5]. The CNS was carbonized in a furnace at 250 °C for 3 h [5], [42]. This temperature falls within the range commonly reported for mild carbonization or torrefaction of biomass. Previous studies have shown that thermal treatment between 200 and 300 °C promotes partial devolatilization and thermal degradation of biomass constituents, particularly hemicellulose, thereby improving fuel properties [43], [44]. Protective hand gloves and nose masks were used during the carbonization process to minimize exposure to cashew nut shell liquid compounds. The carbonized cashew nut shell is shown in Figure 1. Cassava starch, obtained from the main community market in Ilorin, was used as the binder due to its availability and its reported ability to improve the mechanical properties of briquettes [45], [46].



Figure 1: Carbonized cashew nut shell

### 2.2 Briquettes sample preparation and production

The carbonized cashew nut shell was pulverized and sieved to a particle size of 0.2 mm using a standard sieve to obtain a homogeneous biomass. Briquettes were produced according to the methods of Ajimotokan *et al.* [46] and Olaodosu *et al.* [47], with slight modifications. The sieved carbonized cashew nut shell was mixed with 20 g of cassava starch binder. The starch was first dispersed in 40 cm<sup>3</sup> of water and subsequently added to 100 cm<sup>3</sup> of boiling water at 100 °C to obtain a smooth and homogeneous binder solution. The starch concentration used falls within the range previously reported to provide good mechanical properties in briquettes [45], [46]. The briquettes were compacted at a pressure of 5 MPa with a holding time of 5 min to minimize spring-back after compression. The prepared carbonized biomass mixture was fed into the mould, and briquettes were produced in triplicate. Cylindrical briquettes with dimensions of 50 mm diameter and 45 mm height were produced. Briquette production was carried out in the Department of Mechanical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria. Figure 2 shows the produced carbonized cashew nut shell briquettes.



Figure 2: Carbonized cashew nut shell briquettes

### 2.3 Drying of carbonized cashew nut shell briquettes

The produced briquettes were separately placed in open sun, passive solar dryer, and active solar dryer and dried between 9:00 a.m. and 5:00 p.m. in March 2025. The open sun drying was conducted under ambient environmental conditions, while the passive solar dryer operated based on natural convection. In contrast, the active solar dryer was operated under forced convection at an air velocity of 1.5 m/s. Both the passive and active solar dryers were locally fabricated using galvanized steel sheets and Pyrex glass. The transparent glass cover allows solar radiation to penetrate into the drying chamber, while the absorber surface of the drying chamber was coated

black to enhance solar energy absorption. The two dryers were designed with identical dimensions, as presented in Figure 3a. However, the active solar dryer was equipped with a blower to facilitate forced air circulation. The schematic representations of the passive and active solar dryers are shown in Figures 3b and 3c, respectively. During drying, the mass of each briquette was measured at 60-minute intervals using an OHAUS C-series digital weighing balance (accuracy: 0.01 g) until a constant mass was achieved. Relative humidity, ambient temperature, and air velocity were monitored throughout the drying process. In addition, the internal temperatures of the solar dryers were recorded to assess the drying conditions.

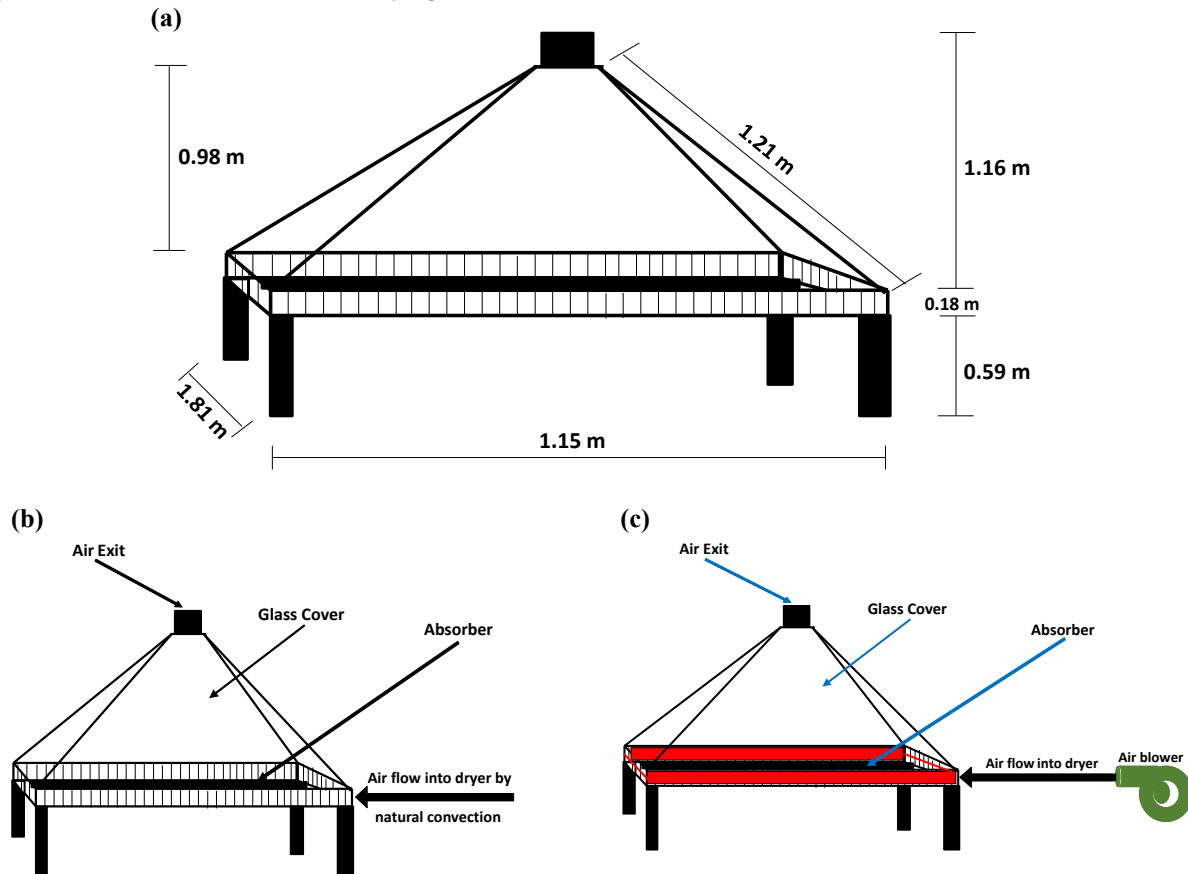


Figure 3: Schematics showing (a) dimensions of both dryers (b) passive solar dryer (c) active solar dryer

## 2.4 Drying Kinetic of the Carbonized Cashew Nut Shell Briquettes

The experimental data were analyzed to determine the moisture ratio, drying rate and effective moisture diffusivity.

### 2.4.1 Moisture ratio

Moisture ratio is defined as the ratio of the moisture content of the sample at any time to the initial moisture content, expressed on a dry basis:

$$M_R = \frac{M_t - M_e}{M_o - M_e} \quad (1)$$

where  $M_R$  is the moisture ratio,  $M_t$  is the moisture content at time  $t$ , and  $M_o$  and  $M_e$  are the initial and equilibrium moisture contents, respectively. For long drying periods, the value of  $M_e$  is negligible compared to  $M_t$  and  $M_o$ . Therefore, the moisture ratio can be simplified as:

$$M_R = \frac{M_t}{M_o} \quad (2)$$

The moisture content at any time on a dry basis is calculated as:

$$M_t = \frac{W_t - W_d}{W_d} \quad (3)$$

where  $W_t$  is the mass of the sample at time  $t$  and  $W_d$  is the mass of the absolutely dry sample.

### 2.4.2 Drying rate

The drying rate is defined as the rate at which moisture is removed from the sample and was calculated using Equation (4) [24]:

$$D_R = \frac{M_{t+dt} - M_t}{dt} \quad (4)$$

where  $D_R$  is the drying rate (g water/g dry matter. min),  $M_{t+dt}$  is the moisture content at time  $t+dt$ , and  $dt$  is the time interval (min).

### 2.4.3 Effective moisture diffusivity

Effective moisture diffusivity explains how fast moisture moves from the inside of the samples to the surface during drying. The effective moisture diffusivity for the drying of the briquettes was calculated using the Fick’s Second Law of diffusion with the assumptions of moisture migration being by diffusion, negligible shrinkage, constant diffusion coefficient and temperature [33]. Equation (5) shows the relationship between moisture ratio, time and effective moisture diffusivity for a cylindrical shaped material [48]:

$$\ln M_R = \ln \frac{4}{b^2} - \frac{b^2 D_{eff}}{R^2} t \tag{5}$$

where  $M_R$  is the moisture ratio,  $R$  is the thickness (m) of the briquette,  $D_{eff}$  is the effective moisture diffusivity ( $m^2 s^{-1}$ ),  $t$  is the drying time (s) and  $b$  is the first positive root of the zero-order Bessel function of the first kind ( $b = 2.4048$ ) [49]. The effective moisture diffusivity of the sample was determined by plotting the graph of  $\ln(MR)$  against  $t$  and the  $D_{eff}$  was calculated from the slope ( $X_1$ ) of the graph using Equation (6):

$$\text{Slope } (X_1) = \frac{D_{eff} b^2}{R^2} \tag{6}$$

### 2.5 Thin layer mathematical modeling of drying kinetics

Thin layer mathematical drying models were used to describe the drying kinetics of the briquettes. Experimental data of moisture ratio against drying time were fitted to the thin layer drying models shown in Table 1 to describe the drying kinetics of briquettes. These twelve models have previously been reported to adequately describe the drying kinetics of agricultural products and biomass materials [24], [25], [27], [29], [32], [50]. The coefficient of determination ( $R^2$ ), sum of square error (SSE), root mean square error (RMSE) and Chi-square ( $\chi^2$ ) are the statistical parameters used as criteria to determine the model that best fit the moisture ratio – time data. The model that has the highest value of  $R^2$  and lowest values of SSE, RMSE and  $\chi^2$  best describe the experimental data [50]. The values of SSE, RMSE and  $\chi^2$  were calculated from Equations (7), (8) and (9), respectively, using Microsoft Excel, while  $R^2$  values were computed using the Excel RSQ function.

$$SSE = \frac{1}{N} \sum_{i=1}^N (M_{R,pred,i} - M_{R,exp,i})^2 \tag{7}$$

$$RMSE = \left[ \frac{1}{N} \sum_{i=1}^N (M_{R,pred,i} - M_{R,exp,i})^2 \right]^{\frac{1}{2}} \tag{8}$$

$$\chi^2 = \frac{\sum_{i=1}^N (M_{R,pred,i} - M_{R,exp,i})^2}{N - Z} \tag{9}$$

where  $M_{R,pred,i}$ ,  $M_{R,exp,i}$ ,  $z$  and  $N$  are the predicted moisture ratio, experimental moisture ratio, number of constants and number of observations, respectively.

Table 1: Thin layer drying models fitted to drying data

No	Model Name	Model equation	References
1.	Midilli-Kucuk	$MR = a \exp(-kt^n) + bt$	[51]
2.	Page	$MR = \exp(-kt^n)$	[52]
3.	Logarithmic	$MR = a \exp(-kt) + c$	[53]
4.	Two-term	$MR = a \exp(-k_0t) + b \exp(-k_1t)$	[54, 55]
5.	Wang and Singh	$MR = 1 + at + bt^2$	[56]
6.	Approximation of diffusion	$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$	[57]
7.	Modified Henderson and Pabis	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$	[58]
8.	Modified Page	$MR = \exp(-(kt)^n)$	[59]
9.	Henderson and Pabis	$MR = a \exp(-kt)$	[60]
10.	Two-term exponential	$MR = a \exp(-kt) + (1 - a) \exp(-kat)$	[61]
11.	Verma <i>et al.</i>	$MR = a \exp(-kt) + (1 - a) \exp(-gt)$	[62]
12.	Weibull <i>et al</i>	$MR = a - b \exp(-kt^n)$	[63]

### 2.6 Proximate analysis of the carbonized cashew nut shell briquettes

Proximate analysis was conducted to determine the moisture content, ash content, volatile matter and fixed carbon of the carbonized cashew nut shell briquettes.

### 2.6.1 Determination of moisture contents

Moisture content was determined based on ASTM D3173 standard [64]. Half (0.5) gram of finely grounded powdered sample was oven dried at a temperature of 105 °C for 1 hour and then taken out, cooled in a desiccator and weighed [46]. The percentage of moisture content (wet basis) is expressed using Equation (10):

$$M_c = \left( \frac{x_1 - x_2}{x_1} \right) \times 100 \quad (10)$$

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).

### 2.6.2 Determination of volatile matter

The volatile matter content of the ground samples was determined using the standard method ASTM D3175-17 [65]. In this method, a clean, dry crucible of known mass was charged with approximately 1 g of the sample and oven-dried to a constant mass. The dried sample was then placed in a covered crucible (with a fitted lid) to prevent contact with air during the release of volatile components. The covered crucible was heated in a muffle furnace at 900 °C for 7 min [46]. After heating, the crucible was removed, cooled in a desiccator, and weighed. The percentage of volatile matter ( $V_m$ ) was calculated using Equation (11):

$$V_m = \frac{\Delta m}{m_i} \times 100 \quad (11)$$

where  $V_m$  is the percentage of volatile matter,  $\Delta m$  is the loss in mass (g), and  $m_i$  is the initial mass of the oven-dried sample (g).

### 2.6.3 Determination of ash content

One gram of each pulverized sample was measured and then placed in a crucible of known mass, then oven-dried to a constant mass. The oven-dried samples were heated in a muffle furnace at 800 °C for 5 h in accordance with ASTM D5142-02 [66] and then allowed to cool in a desiccator before being weighed. The remaining residue was considered ash, and the percentage ash content was calculated using Equation (12):

$$A_c = \frac{M_f}{M_i} \times 100 \quad (12)$$

where  $A_c$  is the ash content in percentage,  $M_i$  is the initial mass of the sample (before burning) and  $M_f$  is the final mass of the sample (after burning).

### 2.6.4 Determination of fixed carbon

The fixed carbon ( $F_c$ ) of the sample was determined by subtracting the sum of the moisture content, volatile matter and ash content (wt. %) from 100 according to Equation (13) [5]:

$$F_c = 100 - [M_c + A_c + V_m] \quad (13)$$

## 2.7 Ultimate analysis

Ultimate analysis is useful for estimating the elemental composition of fuels and is essential for heat and material balance calculations in thermochemical processes. In this study, the elemental composition of the briquette was estimated from the proximate analysis data using established empirical correlations, as presented in Equations (14), (15), (16) and (17). The results were evaluated at an estimated confidence level of 95% [46]:

$$C = 0.637 F_c + 0.455 V_m \quad (14)$$

$$H = 0.052 F_c + 0.062 V_m \quad (15)$$

$$O = 0.304 F_c + 0.476 V_m \quad (16)$$

$$N = 2.10 - 0.020 V_m \quad (17)$$

## 2.8 Determination of calorific value

The calorific value of the biomass was determined using an oxygen bomb calorimeter in accordance with ASTM D5865 [67]. A known mass of the sample was combusted in excess oxygen under constant-volume conditions. The heat released during combustion was absorbed by a known mass of water surrounding the combustion chamber. The initial and final temperatures of the water were recorded, and the heat released was calculated using Equation (18):

$$CV = [(M_w C_w + C_{cal}) \Delta T] / m \quad (18)$$

where  $CV$  is the calorific value or  $HHV$  (J/kg),  $M_w$  is the mass of water (kg),  $C_w$  is the specific heat capacity of water (4.182 kJ/kg·°C),  $C_{cal}$  is the calorimeter constant (J/°C),  $\Delta T$  is the temperature rise (°C), and  $m$  is the mass of the sample (kg). The experiment was conducted in triplicate, and the average values were reported [68].

### 3.0 Results and Discussion

#### 3.1 Open sun, passive and active solar drying characteristics of the carbonized cashew nut shell briquettes

The moisture ratio–drying time curves for the open sun, passive solar, and active solar drying of carbonized cashew nut shell briquettes (CCNS-B) are presented in Figure 4a. Moisture removal was achieved in all drying methods, as the moisture ratio decreased progressively with drying time until a constant mass was attained. Drying times of 1260 min (21 h), 1080 min (18 h), and 900 min (15 h) were required for open sun, passive solar, and active solar drying, respectively. The shorter drying time observed in the active solar dryer is attributed to higher drying temperatures and enhanced air circulation, which increased the rate of heat and mass transfer. The temperature ranges in the ambient and passive solar dryers were 32–41 °C and 32–44 °C, respectively, compared with 36–50 °C in the active solar dryer. Similar reductions in drying time for active solar drying compared with open sun and passive solar drying have previously been reported for banana peel biomass [29].

Figure 4b shows the variation of drying rate with drying time for the three drying methods. The drying rate generally decreased with increasing drying time for all cases, indicating the absence of a constant-rate period. Thus, the drying process occurred entirely within the falling-rate period, suggesting that moisture removal was governed predominantly by internal diffusion mechanisms. This implies that the movement of moisture from the interior of the briquettes to the surface controlled the drying process [35]. Similar drying behavior has been reported for various biomass materials such as microalgae, cashew apple pomace, and other agricultural products under open sun and solar drying conditions [24], [35], [69], [70], [71], where drying predominantly occurs in the falling-rate period.

The effective moisture diffusivities for open sun, passive solar, and active solar drying of CCNS-B are presented in Figure 4c. The values obtained were  $4.50 \times 10^{-9}$ ,  $6.42 \times 10^{-9}$ , and  $9.49 \times 10^{-9}$  m<sup>2</sup>/s, respectively. The higher effective moisture diffusivity observed in the solar dryers, particularly in the active system, can be attributed to the elevated drying temperatures and improved airflow conditions, which enhance moisture migration within the briquettes. The effective moisture diffusivity values obtained in this study fall within the typical range of  $10^{-12}$  to  $10^{-6}$  m<sup>2</sup>/s reported for agricultural and biomass materials [72]. Furthermore, the values are comparable to those reported by Oluremi *et al.* [35] for the drying of yellow cashew apple bagasse using similar drying methods, indicating consistency with established literature.

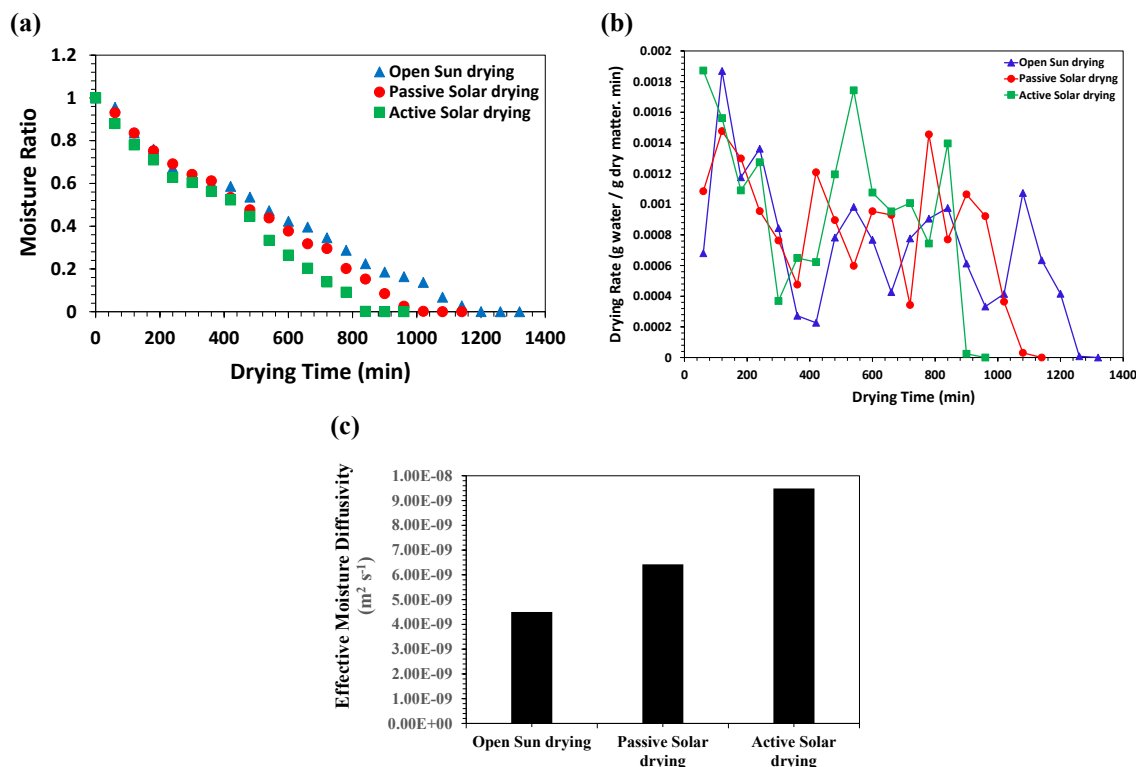


Figure 4: Drying data for the open sun, passive solar and active solar drying of CCNS-B (a) moisture ratio versus drying time (b) drying rate versus drying time (c) effective moisture diffusivity

#### 3.2 Modeling of Drying Kinetics

The twelve thin-layer drying models fitted to the open sun, passive solar, and active solar drying data are presented in Table 2, Table 3 and Table 4, respectively. The statistical parameters obtained from the non-linear regression analysis of these models are also included in these Tables. Model selection was based on maximizing

the coefficient of determination ( $R^2$ ) and minimizing the sum of squared errors (SSE), root mean square error (RMSE), and chi-square ( $\chi^2$ ). Among the models evaluated, the Midilli–Küçük model best described the drying behaviour of CCNS-B under open sun and active solar drying conditions, while the logarithmic model provided the best fit for passive solar drying. These models exhibited the highest  $R^2$  values and the lowest SSE, RMSE, and  $\chi^2$  values. For open sun drying, the Midilli–Küçük model yielded the highest  $R^2$  value of 0.993443, with the lowest SSE (0.000615), RMSE (0.024793), and  $\chi^2$  (0.000744). Similarly, for active solar drying, the model produced an  $R^2$  value of 0.990306, along with the lowest SSE (0.000948), RMSE (0.030793), and  $\chi^2$  (0.001240). For passive solar drying, the logarithmic model performed best, with the highest  $R^2$  value of 0.994253 and corresponding lowest values of SSE (0.000574), RMSE (0.023967), and  $\chi^2$  (0.000676). The Midilli–Küçük and logarithmic models have previously been reported to adequately describe the open sun and solar drying kinetics of several biomass materials [25, 29, 32] and poultry litter briquettes [38].

Table 2: Constants and statistical parameters of models fitted to drying data for the open sun drying of CCNS-B

Model Name	Model Constant	$R^2$	SSE	RMSE	$\chi^2$
<b>Midilli-Kucuk</b>	<b>a=1.0094, b=-0.0003, k=0.0030, n=0.7980</b>	<b>0.993443</b>	<b>0.000615</b>	<b>0.024793</b>	<b>0.000744</b>
Page	k=0.0002, n=1.3351	0.974335	0.002537	0.050368	0.002779
Logarithmic	a=1.7532, c=-0.7719, k=0.0007	0.992674	0.000687	0.026205	0.000790
Two-term	a=1.1012, b=-0.1012, k0=0.0019, k1=0.4504	0.961348	0.003968	0.062994	0.004804
Wang and Singh	a=-4.8363E-10, b=-7.83249E-07	0.858307	0.050597	0.224938	0.055416
Approximation of diffusion	a=-0.1012, b=0.0077, k=0.2402	0.961348	0.003968	0.062994	0.004563
Modified Henderson and Pabis	a=-8.8092, b=9.7191, c=0.0897, g=0.0031, h=0.3978, k=0.0034	0.975867	0.002458	0.049582	0.003326
Modified Page	k=0.0016, n=1.3353	0.974336	0.002537	0.050368	0.002779
Henderson and Pabis	a=1.0654, k=0.0018	0.958952	0.004255	0.065232	0.004660
two-term exponential	<b>a=0.0002, k=9.6984</b>	0.964894	0.004802	0.069295	0.005259
Verma <i>et al</i>	a=-12.4450, g=0.0030, k=0.0031	0.973536	0.002646	0.051438	0.003043
Weibull <i>et al</i>	a=-0.7741, b=-1.7552, k=0.0007, n=1	0.992674	0.000687	0.026205	0.000831

Table 3: Constants and statistical parameters of models fitted to drying data for the passive drying of CCNS-B

Model Name	Model Constant	$R^2$	SSE	RMSE	$\chi^2$
Midilli-Kucuk	a=0.9964, b=-0.0004, k=0.0012, n=0.9445	0.994201	0.000580	0.024075	0.000725
Page	k=9.387E-05, n=1.4684	0.975919	0.002596	0.050954	0.002885
<b>Logarithmic</b>	<b>a=2.2516, c=-1.2621, k=0.0005</b>	<b>0.994253</b>	<b>0.000574</b>	<b>0.023967</b>	<b>0.000676</b>
Two-term	a=1.1329, b=-0.1329, k0=0.0021, k1=0.4504	0.953707	0.005099	0.071407	0.006374
Wang and Singh	a=-0.0013, b=1.2412E-07	0.991842	0.011306	0.106328	0.012562
Approximation of diffusion	a=-21.6378, b=0.9624, k=0.0037	0.972204	0.003006	0.054830	0.003537
Modified Henderson and Pabis	a=-0.6404, b=1.2729, c=0.3676, g=0.0023, h=0.3978, k=0.0192	0.960609	0.387434	0.622442	0.553477
Modified Page	k=0.0018, n=1.4686	0.975921	0.002596	0.050954	0.002885

Model Name	Model Constant	R <sup>2</sup>	SSE	RMSE	χ <sup>2</sup>
Henderson and Pabis	a=1.0813, k=0.0020	0.949271	0.005637	0.075078	0.006263
two-term exponential	a=1.0182E-05, k=183.2550	0.957495	0.006526	0.080786	0.007252
Verma <i>et al</i>	a=9.088660, g=0.0038, k=0.0035	0.972100	0.003012	0.054882	0.003544
Weibull <i>et al</i>	a=-1.260664, b=-2.2490, k=0.0005, n=1.0031	0.994246	0.000575	0.023981	0.000719

Table 4: Constants and statistical parameters of models fitted to drying data for the active solar drying of CCNS-B

Model Name	Model constants	R <sup>2</sup>	SSE	RMSE	χ <sup>2</sup>
<b>Midilli-Kucuk</b>	<b>a=0.9995, b=-0.0009, k=0.0151, n=0.4039</b>	<b>0.990306</b>	<b>0.000948</b>	<b>0.030793</b>	<b>0.001240</b>
Page	k=0.0001, n=1.4357	0.964404	0.003773	0.061423	0.004276
Logarithmic	a=2.8264, c=-1.8611, k=0.0005	0.989390	0.001038	0.032215	0.001260
Two-term	a=1.1122, b=-0.1122, k0=0.0025, k1=0.4504	0.939520	0.006267	0.079162	0.008195
Wang and Singh	a=-0.0013, b=1.3812E-07	0.988595	0.001870	0.043247	0.002120
Approximation of diffusion	a=-0.1007, b=0.0113, k=0.2124	0.941254	0.006249	0.079050	0.007588
Modified Henderson and Pabis	a=-20.3121, b=21.0730, c=0.2391, g=0.0046, h=0.3978, k=0.0048	0.971125	0.003136	0.056000	0.004847
Modified Page	k=0.0021, n=1.4359	0.964408	0.003773	0.061423	0.004276
Henderson and Pabis	a=1.0574, k=0.0023	0.938546	0.006587	0.081162	0.007466
two-term exponential	a=1.6570E-05, k=131.8488	0.944764	0.007052	0.083978	0.007993
Verma <i>et al</i>	a=-170.2958, g=0.0030, k=0.0031	0.956539	0.005737	0.075744	0.006967
Weibull <i>et al</i>	a=-8.6118, b=-9.5952, k=0.0003, n=0.8716	0.989914	0.000987	0.031415	0.001291

### 3.3 Proximate and ultimate characteristics of the carbonized cashew nut shell briquettes

The proximate and ultimate compositions of carbonized cashew nut shell briquettes subjected to different drying methods are presented in Table 5. The results show that the drying method had a noticeable influence on the proximate properties of the briquettes, while only marginal variations were observed in the ultimate composition. The moisture content decreased progressively from open sun drying (2.68%) to passive solar drying (2.50%) and was lowest in active solar drying (2.01%). The lower moisture content observed in the active solar dryer can be attributed to the continuous circulation of heated air, which enhances heat and mass transfer, maintains a strong evaporation gradient, and limits moisture re-absorption. The moisture contents obtained in this study are lower than the 4.59% reported by Tuates Jr *et al.* [73], indicating improved drying efficiency.

A similar decreasing trend was observed for volatile matter, with values of 55.2%, 53.11%, and 51.04% for open sun, passive solar, and active solar drying, respectively. The reduction in volatile matter with increasing drying intensity may be attributed to the partial thermal degradation and loss of light volatile compounds at elevated drying temperatures, particularly from the starch binder. The volatile matter values obtained in this study are higher than 46.59% reported by Tuates Jr *et al.* [73], but lower than 78.74% reported by Fombu *et al.* [74], reflecting differences in feedstock treatment and processing conditions.

The ash content ranged from 6.87% to 8.33%, with the lowest value observed in passive solar drying (6.87%) and the highest in active solar drying (8.33%). Although ash content is generally independent of drying conditions, the slightly higher value observed in the active solar-dried briquettes is likely due to a relative concentration effect resulting from the reduction in moisture and volatile components rather than an actual increase in mineral content. The ash values obtained fall within the range of 5–10% reported by Kimutai and Kimutai [42] and are comparable to 0.37–7.69% reported by Sarafa *et al.* [5].

The fixed carbon content increased from 35.17% (open sun) to 37.52% (passive solar) and 38.62% (active solar), which is consistent with the observed reduction in volatile matter. This increase suggests that active solar drying enhances the carbon-rich fraction of the briquettes, thereby improving fuel quality. The fixed carbon values obtained are lower than 46.59% reported by Tuates Jr *et al.* [73] but higher than the range of 28–32% reported by Pathaveerat *et al.* [75]. Higher fixed carbon content is associated with improved combustion characteristics and higher energy output, as reported by Kimutai and Kimutai [42].

The ultimate analysis results show minimal variation across the drying methods, indicating that the elemental composition of the briquettes is largely unaffected by the drying process. The carbon content ranged narrowly between 47.52% and 48.07%, confirming the uniformity of the base material. The slightly higher carbon content observed in the passive solar-dried sample may be associated with its lower ash content; however, the differences are not significant. High carbon content is indicative of good fuel quality and enhanced calorific value, consistent with findings by Ismaïla *et al.* [76] and Sarafa *et al.* [5].

The hydrogen content ranged from 5.17% to 5.25%, showing a slight decrease with increasing drying intensity, which may be attributed to minor loss of moisture-bound hydrogen and light hydrocarbons. These values are consistent with the range of 5.1–5.6% reported by Ajimotokan *et al.* [46]. Lower hydrogen content is advantageous as it reduces the formation of water vapor during combustion [5].

The oxygen content decreased slightly from 36.97% to 36.04% with increasing drying intensity. This trend may be attributed to the removal of oxygenated volatile compounds and moisture during drying. The oxygen values obtained fall within the range of 34.4–41.5% reported by Ajimotokan *et al.* [46]. Although binder addition typically influences oxygen content, the minimal variation observed here suggests that drying conditions, rather than composition, played a more dominant role.

The nitrogen content showed a slight increase from 1.00% to 1.08%, which is likely a relative increase due to the reduction in other components such as volatile matter. The variation is minimal, indicating no significant influence of drying method on nitrogen content. However, nitrogen in biomass fuels is associated with the formation of NO<sub>x</sub> emissions during combustion, which are undesirable due to their environmental and health impacts [42].

Overall, the results indicate that while drying methods significantly influence the proximate composition (particularly moisture, volatile matter, and fixed carbon) the ultimate composition remains largely unchanged. Among the methods evaluated, active solar drying produced briquettes with improved fuel characteristics, including lower moisture content, reduced volatile matter, and higher fixed carbon, making it the most effective drying method for enhancing briquette quality.

Table 5: Proximate and ultimate analysis of carbonized cashew nut shell briquettes

Drying Method	MC	VM	AC	FC	C	H	O	N
Sun	2.68	55.2	6.95	35.17	47.52	5.25	36.97	1.00
Passive Solar	2.50	53.11	6.87	37.52	48.07	5.24	36.69	1.04
Active Solar	2.01	51.04	8.33	38.62	47.82	5.17	36.04	1.08

### 3.4. Heating value, fuel ratio and volatile ignitability of the carbonized cashew nut shell briquettes

The Higher Heating Value (HHV), Fuel Ratio (FR), and Volatile Ignitability (VI) of the carbonized cashew nut shell briquettes (CCNS-B) under different drying methods are presented in Table 6. The results show that there is no significant difference in the heating values of the briquettes across the drying methods, although a slight increase was observed with increasing drying intensity. This indicates that the drying method has minimal direct influence on the intrinsic energy content of the briquettes but significantly affects the moisture content and, consequently, the effective energy utilization.

Among the drying methods, the active solar-dried briquettes exhibited the highest HHV of 25.76 MJ/kg, followed by passive solar (25.23 MJ/kg) and open sun drying (25.18 MJ/kg). The higher heating value observed in the active solar drying can be attributed to the lower moisture content, reduced volatile matter, and higher fixed carbon content achieved under enhanced drying conditions. Similar trends have been reported by Tuates Jr *et al.* [73], Chinyere *et al.* [77], and Putri *et al.* [78], where a decrease in moisture and volatile matter, coupled with an increase in fixed carbon, resulted in improved heating values. The HHV values obtained in this study are higher than 23.04 MJ/kg reported by Tuates Jr *et al.* [73], lower than 29.55 MJ/kg reported by Fombu *et al.* [74], and comparable to 25.69 MJ/kg reported by Huko *et al.* [79], indicating that the produced briquettes possess good fuel quality. The relatively high HHV values obtained suggest that the briquettes can generate sufficient heat for domestic cooking and heating applications, while also improving fuel efficiency and reducing the quantity of fuel required during combustion.

The fuel ratio of the briquettes increased from 0.64 (open sun) to 0.71 (passive solar) and 0.76 (active solar). This increase is directly related to the increase in fixed carbon and corresponding decrease in volatile matter, as

the fuel ratio is defined as the ratio of fixed carbon to volatile matter. The higher temperature and improved drying efficiency in the active solar dryer contributed to this trend by promoting the reduction of volatile components. The obtained fuel ratio values fall within the recommended range of  $0.5 \leq FR \leq 2.0$  [20], indicating that the briquettes are suitable for combustion applications, including domestic and industrial energy systems [80]. The relatively moderate fuel ratio suggests a balanced combustion behavior with adequate ignition and sustained burning characteristics.

The volatile ignitability (VI) values obtained for open sun, passive solar, and active solar drying were 22.97, 22.56, and 23.95 MJ/kg, respectively. The higher VI observed in the active solar-dried briquettes may be attributed to their higher heating value, which compensates for the slight reduction in volatile matter. All the briquettes exceeded the minimum recommended VI value of 14.5 MJ/kg required for effective ignition in solid fuel combustion systems, indicating that the produced briquettes possess good ignition characteristics and are suitable for both domestic and industrial energy applications.

Table 6: Higher heating value, fuel ratio and volatile ignitability of the CCNS-B

Sample	HHV (MJ/kg)	FR	VI (MJ/kg)
Open Sun	25.18	0.64	22.97
Passive Solar	25.23	0.71	22.56
Active Solar	25.76	0.76	23.95

HHV = Higher Heating Value, FR = Fuel Ratio, VI = Volatile Ignitability

#### 4.0 Conclusion

This study evaluated the effect of open sun, passive solar, and active solar drying on the drying kinetics and fuel properties of carbonized cashew nut shell briquettes. The results demonstrated that drying method significantly influenced moisture removal behaviour and combustion characteristics, while having minimal effect on the ultimate elemental composition.

Active solar drying was the most efficient method, producing briquettes with the lowest moisture content (2.01%) and shortest drying time (900 min), compared to passive solar and open sun drying. The drying process occurred entirely within the falling-rate period, confirming that internal moisture diffusion was the dominant mechanism controlling moisture movement. Effective moisture diffusivity increased with drying intensity, with the highest value obtained under active solar conditions, indicating enhanced mass transfer due to elevated temperature and improved airflow.

Among the twelve thin-layer drying models evaluated, the Midilli-Kucuk model provided the best fit for the open sun and active solar drying while the Logarithmic model best described the passive solar drying kinetics. In terms of fuel properties, active solar drying improved proximate characteristics by reducing volatile matter and increasing fixed carbon, thereby enhancing combustion performance. Although slight variations were observed in ash, carbon, hydrogen, oxygen, and nitrogen contents, the ultimate analysis confirmed that drying method does not significantly alter elemental composition.

The higher heating value ranged from 25.18 to 25.76 MJ/kg, with the highest value obtained from active solar drying, indicating improved energy quality under enhanced drying conditions. Fuel ratio and volatile ignitability values also confirmed good combustion suitability for all samples.

Overall, active solar drying was identified as the most effective method for producing high-quality carbonized cashew nut shell briquettes using renewable solar energy. The findings of this study provide useful insights for optimizing biomass drying systems and support the development of efficient, sustainable solid biofuels from agricultural residues.

#### References

- [1] L. Gnanasekaran, A. K. Priya, S. Thanigaivel, T. K. A. Hoang, and M. Soto-Moscoso, "The conversion of biomass to fuels via cutting-edge technologies: Explorations from natural utilization systems," *Fuel*, vol. 331, pt. 1, p. 125668, 2023, doi: 10.1016/j.fuel.2022.125668.
- [2] P. Rijal, H. Carvalho, J. Matias, S. Garrido, and C. Pimentel, "Drivers and barriers of residual agroforestry biomass valorization: A systematic literature review," *Agroforestry Systems*, vol. 99, p. 81, 2025, doi: 10.1007/s10457-024-01131-2.
- [3] M. Röder, K. Chong, and P. Thornley, "The future of residue-based bioenergy for industrial use in Sub-Saharan Africa," *Biomass and Bioenergy*, vol. 159, p. 106385, 2022, doi: 10.1016/j.biombioe.2022.106385.
- [4] J. Guo, Y. Zhang, J. Fang, Z. Ma, C. Li, M. Yan, N. Qiao, Y. Liu, and M. Bian, "Reduction and reuse of forestry and agricultural bio-waste through innovative green utilization approaches: A review," *Forests*, vol. 15, no. 8, p. 1372, 2024, doi: 10.3390/f15081372.

- [5] I. Sarafa, O. S. Olaoye, E. O. Olafimihan, K. O. Oladosu, K. A. Babatunde, J. T. Oladeji, and K. K. Salam, "Production and characterization of cashew nut shell and sugarcane bagasse composite briquettes as an alternative energy source," *International Journal of Advances in Engineering and Management*, vol. 4, no. 9, pp. 1177–1186, 2022.
- [6] D. K. Gari, V. R. Ancha, and Y. B. Tola, "Dehydration of biomass charcoal briquettes using a modified solar tunnel drying system: An experimental and CFD approach," *Case Studies in Thermal Engineering*, vol. 73, p. 106624, 2025.
- [7] M. Hisjam, S. Hartini, E. F. Aqidawati, H. Sintawati, A. N. Putri, and D. Nurhadiyanto, "Sustainable biomass briquettes adoption in food SMEs: Drivers, barriers, and policy implication in Central Java, Indonesia," *Journal of Sustainability Research*, vol. 8, no. 1, p. e260004, 2026.
- [8] R. Tumpa, S. Sarker, S. Nanda, V. Meda, and A. K. Dalai, "Densification of waste biomass for manufacturing solid biofuel pellets: A review," *Environmental Chemistry Letters*, vol. 21, pp. 231–264, 2023, doi: 10.1007/s10311-022-01510-0.
- [9] S. O. Salifu and S. J. Ibitoye and H. I. Opaluwa, "Growth, performance, and forecasting of cashew nut production in Nigeria (1991–2020)," *International Journal of Agricultural Economics, Management and Development*, 2024.
- [10] Nigerian Export Promotion Council, "NEPC launches organic cashew certification for export," 2023. <https://nepc.gov.ng>
- [11] F. B. Akande, F. A. Ola, K. O. Oriola, T. Iorpev, and I. H. Manta, "Research and development of cashew nut shelling machines in Nigeria: A review," *Journal of Agricultural Mechanization*, vol. 5, no. 1, pp. 46–53, 2025.
- [12] P. K. Alizadeh, L. G. Tabil, P. K. Adapa, D. Cree, E. Mupondwa, and B. Emadi, "Torrefaction and densification of wood sawdust for bioenergy applications," *Fuels*, vol. 3, no. 1, pp. 152–175, 2022, doi: 10.3390/fuels3010010.
- [13] M. K. Zafeer and K. S. Bhat, "Valorisation of agro-waste cashew nut husk (testa) for different value-added products," *Sustainable Chemistry for Climate Action*, vol. 2, p. 100014, 2023.
- [14] T. Cruz, A. Marañón, C. Hernández, O. Álvarez, C. Ayala-García, and A. Porras, "Exploring the potential of cashew nutshells: A critical review of alternative applications," *BioResources*, vol. 19, no. 3, pp. 6768–6803, 2024, doi: 10.15376/biores.19.3.Cruz.
- [15] S. Neeraj, Y. Menon, and A. Sharma, "Transfer of sawdust to chemicals and biofuels," in *Valorization of solid wastes to biofuels and chemical products for a sustainable world*, A. Kumari et al., Eds. Springer, 2025, doi: 10.1007/978-981-96-8594-3\_14.
- [16] G. Paul, M. Olivier, A. Esther, M. Daniel, and C. L. Jean, "Heat and mass transfer local modelling applied to biomass briquette drying," *Procedia Manufacturing*, vol. 35, pp. 149–154, 2019.
- [17] N. N. Chen, M. Q. Chen, B. A. Fu, and J. J. Song, "Far-infrared irradiation drying behavior of typical biomass briquettes," *Energy*, vol. 121, pp. 726–738, 2017.
- [18] R. Walozi, G. S. Onep, Y. S. Sanusi, O. E. Babiker, M. S. Dennison, A. Candia, and S. Okurut, "A comprehensive review of chemical treatments for biomass feedstock to enhance briquette characteristics," *Discover Sustainability*, 2026, doi: 10.1007/s43621-026-03045-8.
- [19] A. K. Ajit, R. Madhuka, and K. Krishnendu, "Densification of biomass by briquetting," *International Journal of Recent Scientific Research*, vol. 8, pp. 20561–20568, 2017.
- [20] M. A. Waheed, O. A. Akogun, and C. C. Enweremadu, "An overview of torrefied bioresource briquettes: Quality-influencing parameters, enhancement through torrefaction, and applications," *Bioresources and Bioprocessing*, vol. 9, no. 1, p. 122, 2022.
- [21] P. Kipngetch, R. Kiplimo, J. K. Tanui, and P. Chisale, "Effects of carbonization on the combustion of rice husk briquettes in a fixed bed," *Cleaner Engineering and Technology*, vol. 13, p. 100608, 2023, doi: 10.1016/j.clet.2023.100608.
- [22] K. Kabango, F. G. D. Thulu, T. Mlowa, C. Chisembe, and C. C. Kaonga, "Effect of carbonisation on combustion characteristics of faecal sludge and sawdust blended briquettes," *Environmental Sustainability*, vol. 6, pp. 331–339, 2023.
- [23] Z. Guo, J. Wu, Y. Zhang, F. Wang, Y. Guo, K. Chen, and H. Liu, "Characteristics of biomass charcoal briquettes and pollutant emission reduction for sulfur and nitrogen during combustion," *Fuel*, vol. 272, p. 117632, 2020.
- [24] O. O. Agbede, E. O. Oke, S. I. Akinfenwa, K. T. Wahab, S. Ogundipe, O. A. Aworanti, A. O. Arinkoola, S. E. Agarry, O. O. Ogunleye, F. N. Osulale, and K. A. Babatunde, "Thin-layer drying of green microalgae (*Chlorella* sp.) paste biomass: Drying characteristics, energy requirement, and mathematical modeling," *Bioresource Technology Reports*, vol. 11, Art. no. 100467, 2020, doi: 10.1016/j.biteb.2020.100467.
- [25] O. O. Agbede, A. O. Adebisi, E. O. Oke, A. O. Arinkoola, O. O. Ogunleye, S. E. Agarry, K. A. Babatunde, and F. N. Osulale, "Thin-layer drying of orange skin paste for biofuel production: Drying characteristics

- and mathematical modelling,” *Nigerian Research Journal of Engineering and Environmental Sciences*, vol. 4, no. 2, pp. 578–592, 2019.
- [26] O. O. Agbede, K. J. Ayanniyi, F. N. Osuolale, E. O. Oke, S. E. Agarry, O. O. Ogunleye, and K. A. Babatunde, “Hot air oven drying of maize husks biomass: Effects of bed depth and temperature on drying kinetics, moisture diffusivity and energy requirement,” *Nigerian Research Journal of Engineering and Environmental Sciences*, vol. 4, no. 2, pp. 991–1005, 2019.
- [27] O. O. Agbede, K. J. Ayanniyi, K. A. Babatunde, F. N. Osuolale, E. O. Oke, O. O. Ogunleye, and S. E. Agarry, “Thin layer modelling of open sun and solar drying kinetics of pulverized maize husks,” *Journal of the Nigerian Society of Chemical Engineers*, vol. 35, no. 1, pp. 71–83, 2020.
- [28] O. O. Agbede, I. S. Odewale, E. O. Oke, and O. A. Aworanti, “Microwave drying of banana (*Musa acuminata*) stalk biomass before conversion to value-added products,” *LAUTECH Journal of Civil and Environmental Studies*, vol. 6, no. 1, pp. 11–25, 2021.
- [29] O. O. Agbede, K. A. Omotola, F. N. Osuolale, O. A. Aworanti, A. O. Arinkoola, K. A. Babatunde, S. O. Alagbe, S. E. Agarry, and O. O. Ogunleye, “Renewable solar energy systems for sustainable drying of banana (*Musa acuminata*) peel biomass,” *African Journal of Engineering and Environment Research*, vol. 4, no. 1, pp. 113–135, 2022.
- [30] O. O. Agbede, G. R. Eniola, K. A. Omotola, O. A. Aworanti, S. E. Agarry, S. O. Alagbe, A. O. Alade, T. J. Afolabi, and G. A. Adebayo, “Artificial neural network and mathematical modelling of the microwave drying of banana peel biomass,” *Nigerian Research Journal of Engineering and Environmental Sciences*, vol. 8, no. 1, pp. 1–17, 2023.
- [31] O. O. Agbede, G. R. Eniola, O. A. Aworanti, F. N. Osuolale, A. O. Arinkoola, S. O. Alagbe, S. E. Agarry, O. O. Ogunleye, K. A. Babatunde, E. O. Dada, and O. D. Akinwumi, “The influence of surface area, temperature and pretreatment on convective hot air oven drying of banana peels biomass,” *Engineering and Applied Science Research*, vol. 50, no. 5, pp. 420–439, 2023.
- [32] O. O. Agbede, I. S. Odewale, O. A. Aworanti, S. O. Alagbe, O. Ogunkunle, and O. T. Laseinde, “Solar and open sun drying of untreated and pretreated banana stalk chips biomass: Sustainable processing using renewable solar energy,” *Discover Food*, vol. 3, Art. no. 17, 2023, doi: 10.1007/s44187-023-00058-4.
- [33] O. O. Agbede, O. A. Ayodeji, O. A. Aworanti, A. S. Oluyemi, O. Ogunkunle, and O. T. Laseinde, “Convective drying characteristics and moisture transfer properties of *Jatropha curcas* L. seeds,” *Scientific African*, vol. 23, Art. no. e02122, 2024, doi: 10.1016/j.sciaf.2024.e02122.
- [34] A. Khalil, A. M. Khaira, R. H. Abu-Shanab, and M. Abdelgaied, “A comprehensive review of advanced hybrid technologies that improve the performance of solar dryers: Photovoltaic/thermal panels, solar collectors, energy storage materials, biomass, and desalination units,” *Solar Energy*, vol. 253, pp. 154–174, 2023, doi: 10.1016/j.solener.2023.02.032.
- [35] I. A. Oluremi, C. O. Oke, S. A. Azeez, A. O. Alamu, S. O. Alagbe, F. N. Osuolale, and O. O. Agbede, “Thin-layer drying of cashew (*Anacardium occidentale* L.) bagasse in an active solar dryer: Drying characteristics and mathematical modeling of drying kinetics,” in *Proc. 6th Int. Conf. Workshop on Engineering and Technology Research (ICWETR) LAUFET 2025*, Ogbomoso, Nigeria: Ladoko Akintola University of Technology, 2025, pp. 436–447.
- [36] S. G. Unar, S. A. Khatri, N. H. Mirjat, P. H. Shaikh, S. A. R. A. Zaidi, and M. F. Arain, “Solar drying technologies: A review of design, efficiency, and environmental impacts,” *Renewable and Sustainable Energy Reviews*, vol. 226, Art. no. 116339, 2026, doi: 10.1016/j.rser.2025.116339.
- [37] P. Morya, M. Agarwal, and G. D. Agarwal, “A comprehensive insight into solar drying systems for agricultural and industrial applications,” *Solar Energy*, vol. 293, Art. no. 113494, 2025, doi: 10.1016/j.solener.2025.113494.
- [38] M. J. Molefe and I. N. Simate, “Thin layer drying and modelling of poultry litter briquettes,” *Energy and Environment Research*, vol. 9, no. 1, pp. 9–17, 2019.
- [39] F. A. Guibunda, S. Waita, F. W. Nyongesa, G. J. Snyder, and J. Chaciga, “Optimizing biomass briquette drying: A computational fluid dynamics approach with a case study in Mozambique,” *Energy 360*, vol. 2, Art. no. 100012, 2024, doi: 10.1016/j.energ.2024.100012.
- [40] A. H. S. Atienza, J. L. A. Bergonio, A. N. J. Refrea, and C. J. T. Velasco, “Passive indirect solar dryer integrated with perforated baffles and thermal storage for drying coconut briquettes,” *Chemical Engineering Transactions*, vol. 122, pp. 61–66, 2025.
- [41] S. Pandey and R. P. Dhakal, “Pine needle briquettes: A renewable source of energy,” *International Journal of Energy Science*, vol. 3, no. 3, pp. 254–260, 2013.
- [42] S. K. Kimutai and I. K. Kimutai, “Investigation of physical and combustion properties of briquettes from cashew nut shell and cassava binder,” *International Journal of Education and Research*, vol. 7, no. 11, pp. 15–26, 2019.

- [43] M. F. Hasan, M. S. Omar, M. A. Sukiran, B. B. Nyakuma, and M. F. Muhamad Said, "Torrefaction of fibrous empty fruit bunch under mild pressurization technique," *Renewable Energy*, vol. 194, pp. 349–358, 2022, doi: 10.1016/j.renene.2022.05.099.
- [44] J. S. Tumuluru, S. Sokhansanj, J. R. Hess, C. T. Wright, and R. D. Boardman, "Review: A review on biomass torrefaction process and product properties for energy applications," *Industrial Biotechnology*, vol. 7, no. 5, pp. 384–401, 2011, doi: 10.1089/ind.2011.7.384.
- [45] E. F. Aransiola, T. F. Oyewusi, J. A. Osunbitan, and L. A. O. Ogunjimi, "Effect of binder type, binder concentration and compacting pressure on some physical properties of carbonized corncob briquette," *Energy Reports*, vol. 5, pp. 909–918, 2019, doi: 10.1016/j.egy.2019.07.011.
- [46] H. A. Ajimotokan, S. E. Ibitoye, J. K. Odusote, O. A. Adesoye, and P. O. Omoniyi, "Physico-mechanical properties of composite briquettes from corncob and rice husk," *Journal of Bioresources and Bioproducts*, vol. 4, no. 3, pp. 159–165, 2019, doi: 10.12162/jbb.v4i3.004.
- [47] K. O. Oladosu, S. A. Babalola, M. W. Kareem, H. A. Ajimotokan, M. Y. Kolawole, W. A. Issa, A. S. Olawore, and E. A. Ponle, "Optimization of fuel briquette made from bi-composite biomass for domestic heating applications," *Scientific African*, vol. 21, Art. no. e01824, 2023, doi: 10.1016/j.sciaf.2023.e01824.
- [48] E. Langovan and S. K. Natarajan, "Experimental research of drying characteristic of red banana in a single slope direct solar dryer," *Food Technology and Biotechnology*, vol. 59, no. 2, pp. 137–146, 2021.
- [49] A. Yağcıoğlu, V. Demir, and T. Günhan, "Effective moisture diffusivity estimation from drying data," *Journal of Agricultural Machinery Science*, vol. 3, no. 4, pp. 249–256, 2007.
- [50] H. Kucuk, A. Midilli, A. Kilic, and I. Dincer, "A review on thin-layer drying-curve equations," *Drying Technology*, vol. 32, no. 7, pp. 757–773, 2014.
- [51] A. Midilli, H. Kucuk, and Z. Yapar, "A new model for single-layer drying," *Drying Technology*, vol. 20, no. 7, pp. 1503–1513, 2002, doi: 10.1081/DRT-120005864.
- [52] G. E. Page, *Factors Influencing the Maximum Rate of Air Drying Shelled Corn in Thin-Layers*, M.S. thesis, Purdue University, West Lafayette, IN, USA, 1949.
- [53] P. K. Chandra and R. P. Singh, *Applied Numerical Methods for Food and Agricultural Engineers*. Boca Raton, FL, USA: CRC Press, 1995.
- [54] S. M. Henderson, "Progress in developing the thin layer drying equation," *Transactions of the ASAE*, vol. 17, pp. 1167–1172, 1974.
- [55] T. L. Glenn, *Dynamic Analysis of Grain Drying System*, Ph.D. dissertation, Ohio State University, Ann Arbor, MI, USA, 1978.
- [56] C. Y. Wang and R. P. Singh, "A single layer drying equation for rough rice," ASAE Paper No. 3001, 1978.
- [57] A. S. Kaseem, "Comparative studies on thin layer drying models for wheat," in *Proc. 13th Int. Congr. Agricultural Engineering*, Morocco, Feb. 2–6, 1998.
- [58] V. T. Karathanos, "Determination of water content of dried fruits by drying kinetics," *Journal of Food Engineering*, vol. 39, no. 4, pp. 337–344, 1999, doi: 10.1016/S0260-8774(98)00132-0.
- [59] G. M. White, T. C. Bridges, O. J. Loewer, and I. J. Ross, "Seed coat damage in thin layer drying of soybeans as affected by drying conditions," ASAE Paper No. 3052, 1978.
- [60] S. M. Henderson and S. Pabis, "Grain drying theory I: Temperature effect on drying coefficient," *Journal of Agricultural Engineering Research*, vol. 6, pp. 169–174, 1961.
- [61] Y. I. Sharaf-Eldeen, J. L. Blaisdell, and M. Y. Hamdy, "A model for ear corn drying," *Transactions of the ASAE*, vol. 23, pp. 1261–1271, 1980.
- [62] L. R. Verma, R. A. Bucklin, J. B. Endan, and F. T. Wratten, "Effects of drying air parameters on rice drying models," *Transactions of the ASAE*, vol. 28, no. 1, pp. 296–301, 1985, doi: 10.13031/2013.32245.
- [63] W. Weibull, "A statistical distribution of wide applicability," *ASME Journal of Applied Mechanics*, vol. 18, pp. 293–297, 1951.
- [64] ASTM International, *ASTM D3173-13: Standard Test Method for Moisture in the Analysis Sample of Coal and Coke*. West Conshohocken, PA, USA: ASTM International, 2013.
- [65] ASTM International, *ASTM D3175-17: Standard Test Method for Volatile Matter in the Analysis Sample of Coal and Coke*. West Conshohocken, PA, USA: ASTM International, 2017.
- [66] ASTM International, *ASTM D5142-02: Standard Test Methods for Proximate Analysis of the Analysis Sample of Coal and Coke by Instrumental Procedures*. West Conshohocken, PA, USA: ASTM International, 2002.
- [67] ASTM International, *ASTM D5865-19: Standard Test Method for Gross Calorific Value of Coal and Coke*. West Conshohocken, PA, USA: ASTM International, 2019.
- [68] A. S. Olabisi, A. O. Balogun, T. O. Oni, B. S. Fakinle, F. Sotoudehnia, A. G. McDonald, and P. P. Ikubanni, "Physicochemical characterization of woody lignocellulosic biomass and charcoal for bio-energy heat generation," *Scientific Reports*, vol. 13, no. 1, p. 19242, 2023.
- [69] E. K. Akpınar, "Mathematical modelling of thin layer drying process under open sun of some aromatic plants," *Journal of Food Engineering*, vol. 77, pp. 864–870, 2006.

- [70] E. K. Akpınar and Y. Bicer, "Mathematical modelling of thin layer drying process of long green pepper in solar dryer and under open sun," *Energy Conversion and Management*, vol. 49, pp. 1367–1375, 2008.
- [71] E. K. Akpınar, "Drying of parsley leaves in a solar dryer and under open sun: Modeling, energy and exergy aspects," *Journal of Food Process Engineering*, vol. 34, pp. 27–48, 2010.
- [72] Z. Erbay and F. İcier, "A review of thin layer drying of foods: Theory, modeling, and experimental results," *Critical Reviews in Food Science and Nutrition*, vol. 50, no. 5, pp. 441–464, 2010, doi: 10.1080/10408390802437063.
- [73] A. M. Tuates Jr., J. M. Suligan, A. R. Ligisan, O. A. Capariño, and J. C. Elauria, "Development of de-oiled cashew nut shell as fuel briquettes," *Journal of the Japan Institute of Energy*, vol. 99, no. 8, pp. 128–135, 2020.
- [74] A. H. Fombu, A. E. Ochonogor, and O. E. Olayide, "Production, characterization, and applications of briquette from cashew nut shell (CNS) bio-char: A form of sustainable development," in *Proc. Sustainable, Clean and Emerging Energy Technologies Conf.*, UNESCO International Centre for Biotechnology, University of Nigeria, Nsukka, Nigeria, 2024.
- [75] S. Pathaveerat, P. Pruengam, and N. Lekrungronggid, "The potential of cashew nut shell waste in charcoal briquettes after producing cashew nut shell liquid through cold extraction," *Results in Engineering*, vol. 23, p. 102579, 2024, doi: 10.1016/j.rineng.2024.102579.
- [76] A. Ismaila, I. Y. Zakari, R. Nasiru, B. I. Tijjani, I. Abdullahi, and N. N. Garba, "Investigation on biomass briquettes as energy source in relation to their calorific values and measurement of their total carbon and elemental contents for efficient biofuel utilization," *Advances in Applied Science Research*, vol. 4, no. 4, pp. 303–309, 2013.
- [77] E. C. Umeocho, C. O. Ezidi, E. N. Nwosu, C. I. Nwankwo, K. C. Ezejiegu, and T. U. Onuegbu, "Comparative study of the combustion properties of briquettes produced from blends of mung beans shell, uncarbonized and carbonized sawdust," *Chemical Reports*, vol. 5, no. 1, pp. 285–290, 2024.
- [78] R. W. Putri, B. S. Rahmatullah, A. Savitri, and M. Zahara, "Effect of drying temperature of sawdust biobriquettes with used lubricant oil adhesive volume variation over carbonization process," *Journal of Ecological Engineering*, vol. 25, no. 2, pp. 309–320, 2024.
- [79] D. Huko, D. N. Kamau, and W. O. Ogola, "Effects of varying particle size on mechanical and combustion characteristics of mango seed shell cashew nut shell composite briquettes," *International Journal of Engineering Science Invention*, vol. 4, no. 5, pp. 32–39, 2015.
- [80] C. Hadey, M. Allouch, M. Alami, F. Boukhelifi, and I. Loulidi, "Preparation and characterization of biochars obtained from biomasses for combustible briquette applications," *The Scientific World Journal*, 2022, Art. no. 2554475, 13 pages, doi: 10.1155/2022/2554475.