



Thermal performance, drying kinetics, and thin-layer model evaluation of a cocoa pod husk briquette-assisted passive solar dryer

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Abstract

Inadequate drying rates and weather dependency remain significant postharvest challenges in conventional solar drying of cocoa (*Theobroma cacao* L.). This study evaluated the thermal performance, drying kinetics, and thin-layer drying model goodness-of-fit of a passive hybrid solar dryer utilizing cocoa pod husk (CPH) briquettes as a renewable auxiliary heat source. Drying trials were conducted under three operating configurations: solar-only, hybrid solar–biomass, and biomass-assisted drying. Temperature, relative humidity, and sample weight were recorded at 30-minute intervals, and dimensionless moisture ratios were fitted to thirteen empirical and semi-empirical thin-layer drying models using nonlinear regression. Model suitability was evaluated using the coefficient of determination (R^2), sum of squared errors (SSE), and root mean square error (RMSE). The hybrid solar–biomass mode established superior thermal performance, generating the highest mean maximum chamber temperature ($59.70 \pm 1.06^\circ\text{C}$) and system drying efficiency (57.80%). While solar-only drying achieved $56 \pm 2.83\%$ moisture reduction over an extended period of 25 h (average drying rate of 0.011 kg/h), the hybrid and biomass-assisted modes reached comparable moisture reduction ($51.00 \pm 1.41\%$ and 50%, respectively) in only 7 h at an accelerated rate of 0.036 kg/h. Among the evaluated models, the Hii model exhibited the best overall fit under solar and hybrid drying regimes (R^2 up to 0.9988, with correspondingly low SSE and RMSE values). The results demonstrate that incorporating CPH briquettes into a passive solar dryer provides effective thermal supplementation, substantially accelerates moisture removal, and promotes circular agricultural waste utilization in cocoa postharvest operations.

Keywords: *Theobroma cacao*, Thin-layer drying models, Drying kinetics, Cocoa pod husk briquette, Passive hybrid solar dryer, Thermal performance

1. Introduction

Cocoa is one of the key commercial cash crops of tropical countries, with the majority of cocoa-based chocolate and some confectionery products being made from it [1]. Cocoa plays an important role in rural livelihood, foreign exchange earnings, and agro-industrial development in many countries, especially in sub-Saharan Africa [2]. Nigeria is still one of the leading producing countries of cocoa in Africa, the acceptability of dried cocoa beans is largely dependent on their quality, both national and international markets [3]. Drying is an important step in postharvest operation with influence on other operations such as drying during the process of cocoa drying, moulding, flavour precursors, acidity, appearance of the beans and storage stability of the beans among others and the most important portion during the processing of cocoa beans, as it affects all other steps in the process [4-6].

The fresh, fertile cocoa beans are rich in moisture and exposed to microbial spoilage, discolouration, and biochemical deterioration if they are not adequately dried [7]. Drying can lower the level of moisture to an acceptable storage level, prevents undesirable microorganisms and promotes desirable sensory characteristics. Cocoa is still traditionally dried using the simple and cheap open sun drying method [8-9]. There are several drawbacks to open sun drying such as the risk of dust, insects, rodents and rainwater contamination and it requires good weather. The process is slow, and frequently uncontrolled leading to insufficient product quality and non-uniform drying results.

The absence of such has led to the studies of solar dryers as good alternatives to drying agricultural products. Solar drying would provide greater environmental protection, increase in the drying efficiency and better quality of the products than the open sun drying. But until now, the use of conventional passive solar dryers has been restrained by the presence of the periodic occurrence of solar radiation. Cloudy conditions, late afternoon, or nights will halt the drying process and extend the drying time and increase the chances of rewetting and quality loss. Discontinuous drying may not be desirable for products which are moisture sensitive, like cocoa.

Hybrid solar dryers are a new concept that has come to the forefront as a potential solution [10]. Hybrid solar dryer is a combination of solar energy and an auxiliary heat source to assure continuous drying from the solar radiation short of availability or adequacy [11]. This is better from the point of view of thermal reliability and lower reliance on fossil fuels. Agricultural residues, when used as alternative heat sources in such a drying system, further reinforce sustainability by reducing the amount of waste. Cocoa pod husk is a by-product of cocoa beans production and it is one of the abundant wastes generated during cocoa processing which is not fully utilized or discarded [12]. The utilization of cocoa pods husk as biomass briquettes is an innovative and eco-friendly solution to help support cocoa drying processes while reducing waste.

The performance of a dryer can be judged by the moisture removal capability and on the other hand by the drying process kinetic [13]. The drying kinetics is important for dryer designs, optimisation, process control and prediction of product behaviour in various operating conditions [9]. Many thin-layer drying models have been proposed for the purpose of describing agricultural materials drying attributes and for obtaining the moisture ratio-drying time relationship, all of which use mathematical representation [14]. However, it is possible to determine the optimal drying behavior for particular materials and drying systems. Different empirical and semi-empirical models like the Newton model, the Page model, the Henderson and Pabis model, the Logarithmic model, the Midili-Kucuk model and the Hii model were successfully applied to food and biological products.

Solar drying of farming products has been reported in several studies but there is dearth in literature on thin-layer drying behaviour of cocoa beans using hybrid passive solar dryer.

The purpose of this study, therefore, was to assess the drying kinetic and properties of fermented cocoa beans in a methodology of drying by solar passive using cocoa pod husk briquette as an auxiliary heat source for the drying process. moisture reduction behaviour, drying rate and moisture ratio patterns were evaluated and existing thin-layer drying models were used to simulate the experimental data. The best fit models were chosen using statistical performance measures such as the coefficient of determination (R^2), sum of squared errors (SSE) and root mean square error (RMSE). Results of this study would enhance the scope of achieving sustainable and continuous drying process to enhance the quality of cocoa and minimize post harvesting losses.

2. Materials and methods

2.1 Design concepts

In a passive hybrid solar dryer, the main components are the collector, the drying chamber and the alternative energy source. 3 mm transparent thick acrylic was selected to cover the dryer in order to trap the solar energy. Figure 1 shows the orthographic and isometric representation of the hybrid solar dryer, respectively. The solar collector was designed slightly tilted on the top of the entire dryer. To achieve a structure that can resist heat loss, metal was used for the framework, which was painted black, it was added with plywood and lagged with an aluminum foil paper to prevent heat loss to the barest minimum. The trays were made of metal and wire mesh to achieve the minimum resistance to airflow, then the product was put in an aluminum tray, which was placed on the wire mesh. At the lower part of the dryer, there is a chamber made for an additional heat source. The design was used to obtain drying data, which was computed into drying equations for modeling the drying kinetics of cocoa with the solar radiation firstly while there was a switch into the use of briquette made up of cocoa pod husk to achieve continuous drying using both solar radiation for daytime drying and briquette for non-sunshine hours.

The drying experiments were conducted under three operating modes: solar drying, using solar radiation as the primary heat source; hybrid solar–biomass drying, combining solar energy with cocoa pod husk briquettes; and biomass-assisted drying, where briquettes provided the principal auxiliary heat during periods of reduced solar input, while ambient solar radiation remained

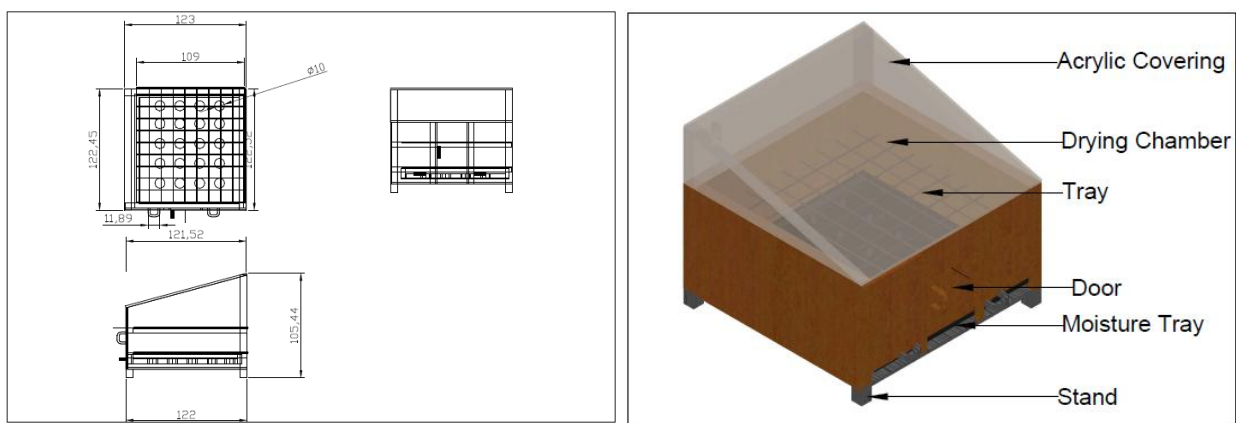


Figure 1 Orthographic and Isometric view of the hybrid dryer

The engineering drawing (Figure 1) indicates the primary dryer dimensions, with an usual length of approximately 123 cm, drying-chamber/collector width of approximately 109–122 cm, and overall chamber peak of about 124.25 cm; the applicable dimensions have now been incorporated into the revised manuscript. The sun collector changed into placed at a slight inclination to facilitate sun-strength collection and natural airflow. The drying trays have been created from twine mesh to minimize resistance to airflow, with the cocoa beans located in aluminium trays.

The experimental method has also been clarified. Temperature and relative humidity were monitored at 30-min durations, whilst ambient conditions had been measured using an Ambient Weather WS-1200 climate station. Air volumetric flow charge changed into determined from the measured outlet air speed and vent pass-sectional area, while mass go with the flow fee changed into calculated from volumetric go with the flow price and air density. The drying test continued thru the sun length and was supplemented by cocoa-pod-husk briquettes after sunset to aid continuous drying. The briquettes were burned in a separate decrease heating chamber, thereby

separating the combustion quarter from the cocoa-bean drying chamber and stopping direct touch between combustion gases and the product.

2.2 Performance evaluation of the hybrid solar dryer

The evaluation of the dryer was centered on the moisture content reduction and temperature variations [15].

No-load Test: No load was carried out in the dryer and the temperature within the dryer was recorded and studied using a datalogger every thirty minutes. The following temperature was taken into consideration; the ambient temperature, the temperature of each trays in the drying chamber and the temperature of the heat storage. The curve of change in air temperature, ambient temperature against time were studied.

Load Test: The load test was carried with fermented cocoa bean using different heat source such as solar, solar with additional heat source and also only heat source. The graph of the various temperature obtained in the no-load test and during the load test will be plotted against time.

Volumetric Flow Rate: This was calculated using the air velocity obtained through an area of the air vent. The air velocity at the outlet and its area was used to the volumetric flow rate of the hybrid solar dryer (Equation 1).

$$\dot{V} = A_c \times v_c \quad (1)$$

where

$\dot{V}$ is the volumetric flow rate (m^3/s)

A_c is the cross sectional area of the air vent (m^2)

v_c is the air velocity at the air vent (m/s)

Mass Flow Rate: With the volumetric flow rate the mass flow rate of air in the dryer can be calculated using the equation below (Equation 2).

$$\dot{m} = \dot{V} \times \rho_a \quad (2)$$

where

$\dot{m}$ is the mass of flow rate (kg/s)

$\dot{V}$ is the velocity of air (m/s)

ρ_a is the density of air (kg/m^3)

Average Drying Rate: This is the measure of the average moisture removal from the product over a specified period. It is the ratio of the mass of moisture over the specified time (Equation 3).

$$m_{dr} = \frac{m_w}{T_d} \quad (3)$$

where

m_{dr} is the average drying rate (kg/h)

m_w is the mass of moisture removed (kg)

T_d is the drying time (h)

System Drying Efficiency: This was calculated as the ratio of the energy required to evaporate the moisture to the heat supplies to the dryer according to Equation 4.

$$n_d = \frac{M \times L}{E_{total}} \quad (4)$$

$$\text{For solar-only mode: } E_{total} = A \cdot I_c \cdot T \quad (4a)$$

$$\text{For Biomass-only mode: } E_{total} = m_b \cdot LHV_b \quad (4b)$$

$$\text{For hybrid (Solar-Biomass) mode: } E_{total} = (A \cdot I_c \cdot T) + (m_b \cdot LHV_b) \quad (4c)$$

Where: n_d is the system drying efficiency

M is the mass of moisture removed (kg)

A is the area of the collector (m^2)

I_c is the insolation on the collector (W/m^2)

L is the Latent heat of evaporation of water (J/kg)

T is the time of drying (sec)

m_b is the mass of briquettes consumed in kg

LHV_b is the Lower Heating Value / Calorific Value of cocoa pod husk briquette in J/kg or MJ/kg , typically $\approx 15.0\text{--}17.5 \text{ MJ/kg}$.

2.3 Experimental set up

In order to collect enough solar energy as much as possible, the hybrid solar dryer was placed in the open with the collector facing south to prevent any shadow being cast on the solar collector surface. An Ambient Weather WS-1200 weather station was placed

outside the dryer to measure the ambient temperature, ambient relative humidity, rainfall wind speed and direction, ultraviolet ray and solar radiation of the environment.

2.4 Drying experiments

The hybrid solar dryer with briquette which serves as an alternative energy source to complete twenty – four hours drying period was used to dry cocoa beans. The experiments were carried out between October – November, 2023. Each drying test was carried out after arranging the fermented cocoa beans in the drying chamber and the drying experiment was continued until sunset. The briquette was put in the briquette chamber and it was ignited at the workshop of the Department of Agricultural and Environmental Engineering, Faculty of Technology, University of Ibadan, Nigeria. The location lies at the latitude of 7°22'39" N, and longitude of 3°54'21" E and altitude of 230m above mean sea level, with an average of solar radiation of 383.89 W/m².

2.5 Moisture content determination

The moisture content was carried out using a convective air oven (DFO -80), which consists of a heating unit, temperature control unit, drying chamber, and centrifugal fan with a fixed air velocity. The average initial moisture content of the cocoa was measured using oven method at a temperature of 135°C for 2 hours until constant weight was reached according to [16]. The moisture content of the cocoa on wet basis (wb) was calculated using Equation 5.

$$MC_{wb} = \frac{W_w}{W_w + W_d} \times 100\% \quad (5)$$

where

MC_{wb} is the Moisture content (% wet basis)

W_w is the weight of water (g)

W_d is the weight of dry matter (g)

Moisture content (wb) was converted to moisture content on dry basis (db) according to Equation 6.

$$MC_{db} = \frac{W_i - W_f}{W_f} \times 100 \quad (6)$$

where

MC_{db} is the moisture content (percentage, dry basis)

W_i is the initial weight before drying (g)

W_f is the final weight after drying (g)

Before the experiment, the dryer was started for one hour to achieve desirable steady state condition and during the experiment, the ambient air temperature, the temperature of the solar dryer, relative humidity, sample weight and sample temperature and sample humidity were initially recorded as the first reading. The temperature and relative humidity of the cocoa beans were monitored at measured at every 30 minutes until the end of the drying period.

2.6 Drying rate

The drying rate of cocoa samples was calculated using Equation 7 [17-18].

$$DR = \frac{M_w}{M_d t} \quad (7)$$

where

DR is the drying rate (kg water/kg Dry Matter-h)

M_w is the mass of moisture removed (kg)

M_d is the mass of dry matter (kg)

t is the drying time (h)

2.7 Moisture ratio

The dimensionless moisture ratio (MR) was calculated using Equation 8 [19].

$$MR = \frac{M - M_e}{M_o - M_e} \quad (8)$$

where

M_o is the Initial moisture content (% dry basis)

M_e is the Equilibrium moisture content (% dry basis)

M is the average moisture content at time t

2.8 Mathematical modelling of drying curves

The drying curve was fitted into thirteen (13) thin layer-drying models that are widely used for most food and biological materials, namely Newton, Henderson and Pabis, Page, Modified Henderson and Pabis, Modified Henderson and Perry, Logarithmic, Two Term,

Silva and et al, Midilli-Kucuk, Hii Model, Modified Page II, Demir and et al. and Hii and et al. The mathematical representations of these models are presented in Table 1

Table 1 Mathematica models of drying curves

Model name	Equation	Reference	Definition of parameters
Lewis (Newton) model	$MR = \exp(-kt)$	Roberts et al. [20]	MR is the moisture ratio (dimensionless) K, g, h are drying constant (h^{-1}) t is the drying time (h) a, b, c, are the drying model constants k, k ₁ , k ₂ are drying constants (h^{-1}) n is Model exponent (dimensionless)
Henderson and Pabis model	$MR = a \exp(-kt)$	Shittu and Raji [21]	
Page model	$MR = \exp(-kt^n)$	Doymaz and Ismail [22]	
Modified Henderson and Pabis model	$MR = -a \exp(-k_1 t^n) + b \exp(-g_1 t) + c$	Corzo et al. [23]	
Modified Henderson and Perry model	$MR = a \exp(-kt^n)$	Ademiluyi et al. [24]	
Logarithmic model	$MR = a \exp(-kt) + c$	Kingsly et al. [25]	
Two Term model	$MR = a \exp(-k_0 t) + b \exp(-k_0 t)$	Kumar et al. [26]	
Silva et al	$MR = \exp(-at - b\sqrt{t})$	Da Silva et al. [27]	
Midilli-Kucuk	$MR = a \exp^{-kt^n} + bt$	Midilli et al. [28]	
Modified Page II	$MR = \exp^{-kt^n}$	Vega et al. [29]	
Demir et al	$MR = a \exp(-kt^n) + b$	Demir et al. [30]	
Hii et al	$MR = a \exp(-k_1 t^n) + b \exp(-k_2 t^n)$	Hii et al. [31]	

2.9 Thin-layer modeling

Non-linear regression analysis using non-linear least squares estimation (Excel Solver / GRG Nonlinear) was used to compute the parameters of the selected drying models. The experimental data was deduced using coefficient of determination (R^2) using sum square error (SSE), and root mean square error (RMSE) which were determined, by using Equations 9 and 10 respectively. Graphical analyses were done by relating the predicted moisture ratio with the estimated data.

$$SSE = \sum_{i=1}^n (MR_{\text{exp } i} - MR_{\text{pred } i})^2 \quad (9)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{\text{exp } i} - MR_{\text{pred } i})^2} \quad (10)$$

where

MR_{exp} is the experimental dimensionless moisture ratio

MR_{pre} is the predicted dimensionless moisture ratio

N is the number of experimental data points, and n is the number of constants

To ensure consistent selection of the best-fit thin-layer drying models, a hierarchical evaluation protocol was established. In instances where statistical criteria diverged such as when a model exhibited the highest coefficient of determination (R^2) but not the absolute lowest sum of squared errors (SSE) or root mean square error (RMSE), the residual error metrics (SSE and RMSE) were strictly prioritized. Although R^2 indicates the proportion of explained variance, it is highly sensitive to the number of model constants and can be artificially inflated. Conversely, SSE and RMSE directly quantify the absolute deviation between predicted and experimental moisture ratios. Prioritizing these residual statistics guarantees that the final selected model possesses the highest physical accuracy and lowest overall model predictive deviation errors.

3. Results

3.1 Meteorological conditions and drying performance characteristics

Tables 2, 3, and 4 present the meteorological, drying chamber, and performance conditions recorded during the experimental drying of fermented cocoa beans using three drying methods. As shown in Table 1, mean solar radiation ranged from 169.45 W/m² to 456.23 W/m² across the experimental periods, reflecting variable but adequate solar energy availability. Table 2 reveals that the Solar–Biomass method produced the highest mean temperature differential ($\Delta T = 17.19 \pm 11.23^\circ\text{C}$), indicating superior heat generation capability over ambient conditions compared to Solar-only ($\Delta T = 15.46^\circ\text{C}$) and Biomass-assisted ($\Delta T = 12.49^\circ\text{C}$) methods. Table 3 further demonstrates that while Solar drying removed the highest moisture content ($56.00 \pm 2.83\%$), the Solar–Biomass and Biomass methods achieved comparable moisture removal (51.00% and 50.00%, respectively) within a significantly shorter drying duration of 7 h compared to 25 h for Solar drying alone, highlighting the efficiency advantage of integrating biomass as a supplementary heat source.

Table 2 Meteorological conditions during experimental drying periods

Drying method	Drying period	Mean solar radiation (W/m ²)	Mean UV intensity ($\mu\text{W}/\text{cm}^2$)	Mean dew point ($^\circ\text{C}$)	Total rainfall (mm)
Solar Drying	7–8 Oct 2023	169.45 $\pm$ 62.34	734.25 $\pm$ 452.18	25.24 $\pm$ 1.12	0.30
Solar Drying	27–28 Oct 2023	456.23 $\pm$ 312.45	1,847.36 $\pm$ 891.24	25.04 $\pm$ 0.98	0.00
Solar–Biomass Drying	1–2 Nov 2023	263.44 $\pm$ 148.67	1,298.25 $\pm$ 612.34	24.78 $\pm$ 0.87	0.30
Biomass Drying	4–5 Nov 2023	246.37 $\pm$ 198.43	756.43 $\pm$ 712.18	24.63 $\pm$ 1.23	16.20
Overall	Oct–Nov 2023	283.87 $\pm$ 219.34	1,159.07 $\pm$ 749.81	24.92 $\pm$ 1.05	16.80

Values expressed as Mean $\pm$ SD; Weather Station: Agricultural and Environmental Engineering, University of Ibadan, Nigeria

Table 3 Drying chamber conditions and ambient conditions by drying method

Parameter	Solar drying	Solar–biomass drying	Biomass drying
Drying Chamber			
Mean Solar Radiation – Tray 1 (W/m ²)	214.34 ± 198.76	318.13 ± 228.43	329.63 ± 219.87
Mean Solar Radiation – Tray 2 (W/m ²)	189.27 ± 186.54	293.25 ± 254.67	274.50 ± 165.34
Mean Temperature – Tray 1 (°C)	45.73 ± 8.67	46.54 ± 12.34	40.93 ± 9.14
Mean Temperature – Tray 2 (°C)	43.26 ± 7.98	44.87 ± 11.21	39.81 ± 8.76
Mean Relative Humidity – Tray 1 (%)	32.94 ± 14.87	40.88 ± 25.78	43.63 ± 9.82
Mean Relative Humidity – Tray 2 (%)	36.61 ± 15.43	43.16 ± 24.87	41.88 ± 11.34
Ambient Conditions			
Mean Ambient Temperature (°C)	29.27 ± 1.38	28.52 ± 1.05	27.88 ± 0.64
Mean Ambient Relative Humidity (%)	74.29 ± 7.21	56.56 ± 26.18	79.13 ± 4.14
Temperature Differential, ΔT (°C)	15.46 ± 7.89	17.19 ± 11.23	12.49 ± 8.57

ΔT = Mean Tray Temperature – Mean Ambient Temperature; Values expressed as Mean ± SD. The duplicate trials ($n = 2$) constitute two independent drying experiments performed at the experimental dates pronounced in Table 2. Each trial corresponds to 1 experimental date, with environmental conditions recorded one after the other for every drying technique. Two unbiased trials had been taken into consideration adequate for preliminary comparative assessment, whilst minimising useful resource necessities and enabling evaluation of consistency throughout experimental dates.

Table 4 Drying performance indicators and moisture loss profile by drying method

Performance parameter	Solar drying	Solar–biomass drying	Biomass drying
General performance			
Initial Sample Weight (kg)	0.500 ± 0.000	0.500 ± 0.000	0.500 ± 0.000
Final Sample Weight (kg)	0.220 ± 0.014	0.245 ± 0.007	0.250 ± 0.000
Total Moisture Removed (kg)	0.280 ± 0.014	0.255 ± 0.007	0.250 ± 0.000
Total Moisture Removed (%)	56.00 ± 2.83	51.00 ± 1.41	50.00 ± 0.00
Total Drying Duration (h)	25.00	7.00	7.00
Mean Drying Rate (kg/h)	0.011 ± 0.001	0.036 ± 0.001	0.036 ± 0.001
Moisture loss profile (Mean sample weight, kg)			
0 h	0.500 ± 0.000	0.500 ± 0.000	0.500 ± 0.000
1 h	0.436 ± 0.018	0.420 ± 0.000	0.408 ± 0.013
2 h	0.413 ± 0.014	0.375 ± 0.007	0.390 ± 0.007
3 h	0.390 ± 0.011	0.330 ± 0.000	0.378 ± 0.018
4 h	0.365 ± 0.018	0.295 ± 0.007	0.365 ± 0.018
5 h	0.340 ± 0.021	0.268 ± 0.011	0.348 ± 0.014
6 h	0.295 ± 0.057	0.255 ± 0.007	0.275 ± 0.064
7 h	0.255 ± 0.035	0.245 ± 0.007	0.250 ± 0.000

Values expressed as Mean ± SD for replicated trials ($n = 2$)

3.2 No-load temperature and relative humidity characteristics

The no-load tests were conducted to evaluate the thermal behaviour of the passive hybrid solar dryer under solar, solar–biomass and briquette-only heating conditions. The temperature profiles showed that the dryer generated temperatures above ambient conditions under all three operating modes. Under solar-only operation, the maximum temperatures recorded in Trays 1 and 2 were 46.2 and 45.1°C, respectively, in Trial 1, and 57.2 and 54.1°C, respectively, in Trial 2. Under the combined solar–biomass mode, maximum temperatures of 57.2 and 57.8°C were recorded in Trays 1 and 2, respectively, during Trial 1, while Trial 2 recorded maximum temperatures of 44.2 and 44.9°C. For briquette-only heating, the maximum temperatures were 49.2 and 53.0°C in Trays 1 and 2, respectively, during Trial 1, and 54.3 and 57.8°C during Trial 2, as shown in Table 5.

The no-load results therefore indicate that the hybrid and briquette heating modes were capable of producing relatively high chamber temperatures, although temperature varied between trials and tray positions. The relative humidity within the drying chamber was generally lower than ambient relative humidity throughout the no-load experiments, indicating that the dryer created a comparatively favourable environment for moisture removal.

The relative humidity results further demonstrate the influence of chamber temperature on the drying environment. As temperature increased above ambient, chamber relative humidity generally decreased, reflecting the greater moisture-holding capacity of warmer air and enhanced moisture removal from the drying chamber. Under no-load conditions, the chamber RH remained below the corresponding ambient RH, indicating that heating promoted a drier internal environment. The effect was particularly evident in the solar mode, where the mean chamber RH was 32.94% and 36.61% in Trays 1 and 2, respectively, compared with ambient RH of 74.29%. For solar–biomass drying, tray RH increased to 40.88% and 43.16%, while ambient RH was 56.56%. This temperature–RH interaction is important because lower chamber RH increases the vapour-pressure gradient, thereby supporting more effective moisture transfer from the cocoa beans to the surrounding air.

Table 5 Statistical summary of no-load maximum temperature by heating mode

Heating mode	Trial	Tray 1 maximum (°C)	Tray 2 maximum (°C)	Mean of tray maxima (°C)	Tray difference (°C)
Solar	1	46.2	45.1	45.65	1.1
Solar	2	57.2	54.1	55.65	3.1
Solar–Biomass	1	57.2	57.8	57.50	-0.6
Solar–Biomass	2	44.2	44.9	44.55	-0.7
Briquette	1	49.2	53.0	51.10	-3.8
Briquette	2	54.3	57.8	56.05	-3.5

Note: Mean of tray maxima and tray differences are calculated from the reported trial values; they are descriptive summaries and not inferential statistics.

3.3 Load test and performance evaluation of the hybrid solar dryer

The results of the loaded drying test showed distinct differences in the thermal behaviour and drying performance of the dryer under solar, solar–biomass, and biomass heating conditions. The performance indicators obtained from the three drying conditions are presented in Table 6.

The solar–biomass drying condition recorded the highest mean maximum temperature of $59.70 \pm 1.06^\circ\text{C}$, followed by biomass drying at $56.00 \pm 0.49^\circ\text{C}$, while solar drying recorded the lowest mean maximum temperature of $54.53 \pm 1.52^\circ\text{C}$. The highest individual temperature of 61.50°C was also recorded under the solar–biomass condition. This indicates that the integration of biomass heating with solar energy enhanced the thermal conditions within the drying chamber.

The initial sample weight was 0.500 ± 0.000 kg for each treatment. Following drying, the solar treatment recorded the lowest final sample weight of 0.220 ± 0.014 kg, corresponding to a moisture removal of 0.280 ± 0.014 kg ($56.00 \pm 2.83\%$). The solar–biomass treatment recorded a final sample weight of 0.245 ± 0.007 kg, representing a moisture removal of 0.255 ± 0.007 kg ($51.00 \pm 1.41\%$), whereas biomass drying resulted in a final sample weight of 0.250 ± 0.000 kg and moisture removal of 0.250 ± 0.000 kg ($50.00 \pm 0.00\%$).

Despite achieving the greatest total moisture removal, solar drying required 25 h to attain the reported final condition. In contrast, both the solar–biomass and biomass treatments attained their respective final conditions within 7 h. The average drying rate was therefore considerably higher for the solar–biomass and biomass treatments (0.036 kg/h) than for solar drying (0.011 kg/h). On the basis of drying duration, the solar–biomass system reduced the drying time by approximately 72% compared with solar drying alone.

The solar–biomass treatment also produced a mean maximum temperature approximately 5.17°C higher than the solar treatment and approximately 3.70°C higher than biomass drying. Although the solar treatment resulted in greater overall moisture removal, the solar–biomass configuration demonstrated a more favourable balance between temperature development and drying time. Its ability to attain a high drying temperature and remove approximately half of the initial sample mass within only 7 h demonstrates the effectiveness of supplementary biomass heating in accelerating the drying process.

The solar–biomass configuration exhibited the most favourable combined thermal and drying performance among the three heating conditions. It produced the highest mean maximum temperature ($59.70 \pm 1.06^\circ\text{C}$), the highest recorded temperature (61.50°C), and achieved rapid drying within 7 h at an average drying rate of 0.036 kg/h. The result demonstrates the potential of integrating biomass heating with solar energy to overcome the limitation of solar-only drying, particularly where solar radiation is insufficient to maintain the desired drying temperature.

Table 6 Statistical summary of load-test and dryer performance

Performance indicator	Solar drying	Solar–biomass drying	Biomass drying
Initial sample weight (kg)	0.500 ± 0.000	0.500 ± 0.000	0.500 ± 0.000
Mean maximum temperature (°C)	54.53 ± 1.52	59.70 ± 1.06	56.00 ± 0.49
Maximum recorded temperature (°C)	57.20	61.50	56.40
Final sample weight (kg)	0.220 ± 0.014	0.245 ± 0.007	0.250 ± 0.000
Moisture removed (kg)	0.280 ± 0.014	0.255 ± 0.007	0.250 ± 0.000
Moisture removed (%)	56.00 ± 2.83	51.00 ± 1.41	50.00 ± 0.00
Drying duration (h)	25.00	7.00	7.00
Average drying rate (kg/h)	0.011	0.036	0.036
Volumetric flow rate (m ³ /s)	0.018	0.021	0.020
Mass flow rate (kg/s)	0.021	0.024	0.023
System drying efficiency (%)	38.60	57.80	53.40

3.4 Goodness-of-Fit evaluation

The model validation results demonstrate that the drying behaviour of fermented cocoa beans was generally well described by the tested thin-layer drying models, although model performance varied with drying condition and tray position. As shown in Figure 2, the models fitted the moisture-ratio data for solar drying in Tray 1 reasonably well, with coefficients of determination (R^2) ranging from 0.9524 to 0.959. The corresponding results for Tray 2 in Figure 3 showed a slightly wider range of R^2 values (0.887–0.9831), indicating a generally strong fit but greater variation among the models.

Under the combined solar–heat condition, Figures 4 and 5 show improved model performance, particularly for Tray 1, where R^2 values ranged from 0.9081 to 0.9981, and Tray 2, where values ranged from 0.374 to 0.9988. The highest R^2 values of 0.9981 and 0.9988 were obtained for Trays 1 and 2, respectively, indicating an excellent agreement between predicted and measured moisture ratios under hybrid drying. For briquette heating alone, Figures 6 and 7 show R^2 ranges of 0.741–0.9711 for Tray 1 and 0.5916–0.9991 for Tray 2, indicating greater variation in model suitability.

Overall, the Hii et al. model provided the best fit among the reported models, particularly under solar and hybrid conditions, with R^2 values of 0.9558 and 0.9981 for Tray 1 and 0.9831 and 0.9988 for Tray 2, respectively. The close agreement between predicted and experimental values in Figures 2–5 indicates that the model can adequately represent the drying kinetics of cocoa beans under these conditions.

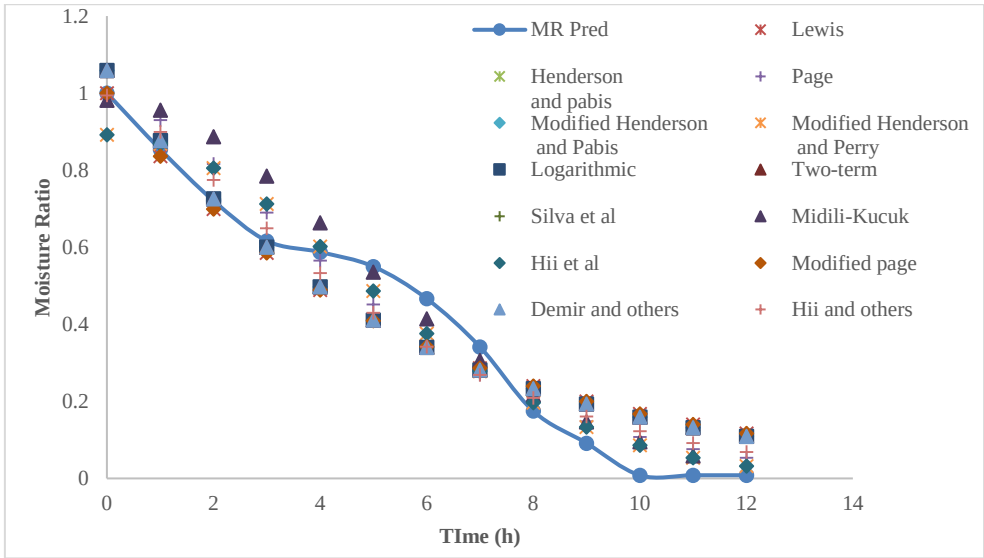


Figure 2: Drying model fitting (solar tray 1)

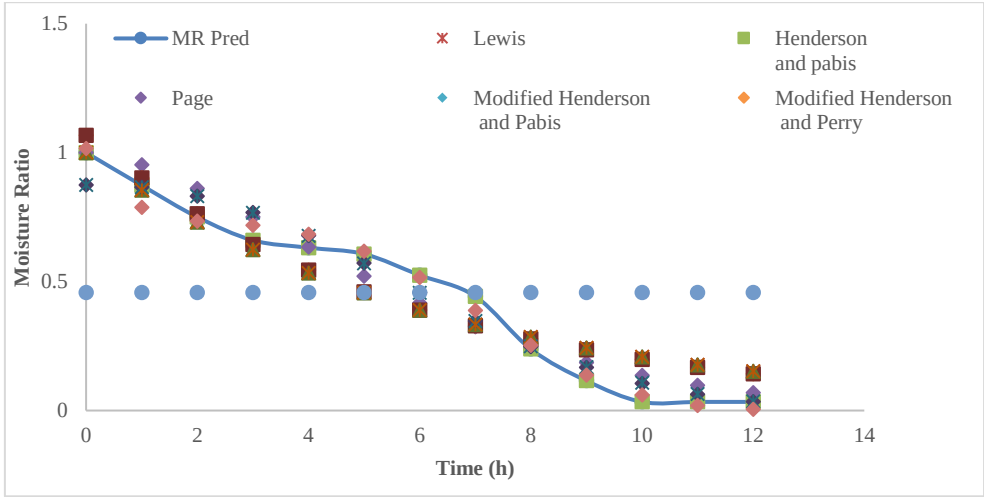


Figure 3: Drying model fitting (solar tray 2)

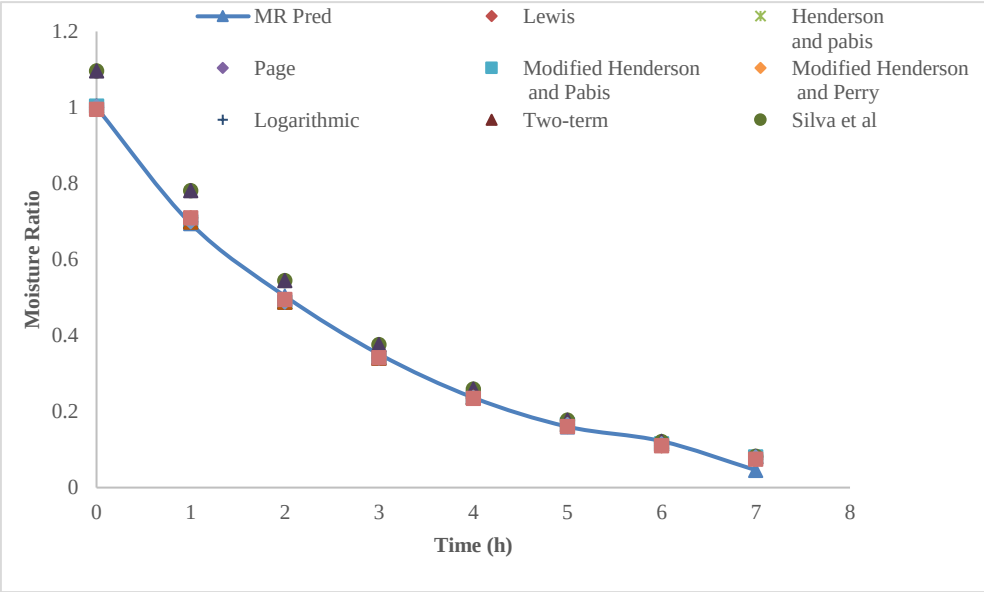


Figure 4: Drying model fitting (heat + solar tray 1)

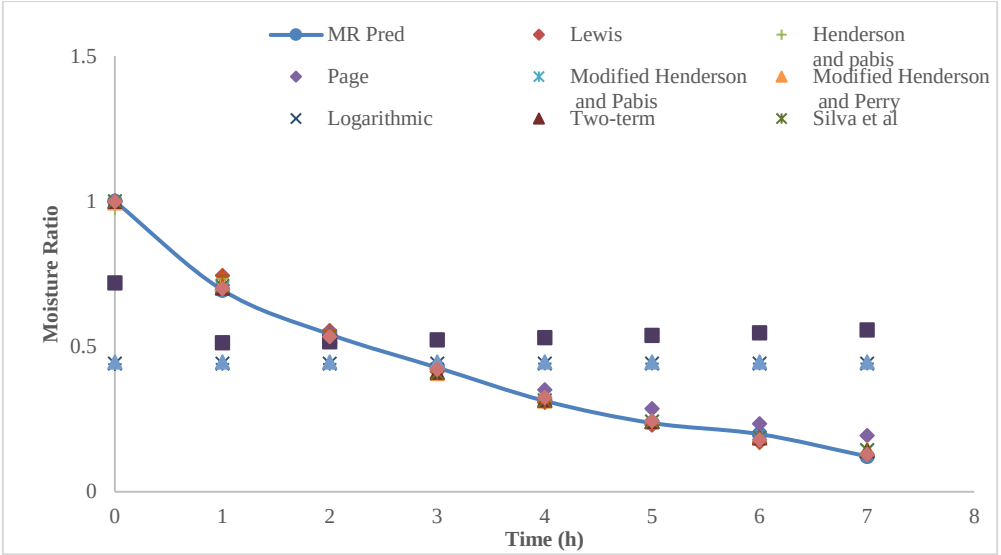


Figure 5: Drying model fitting (heat + solar tray 2)

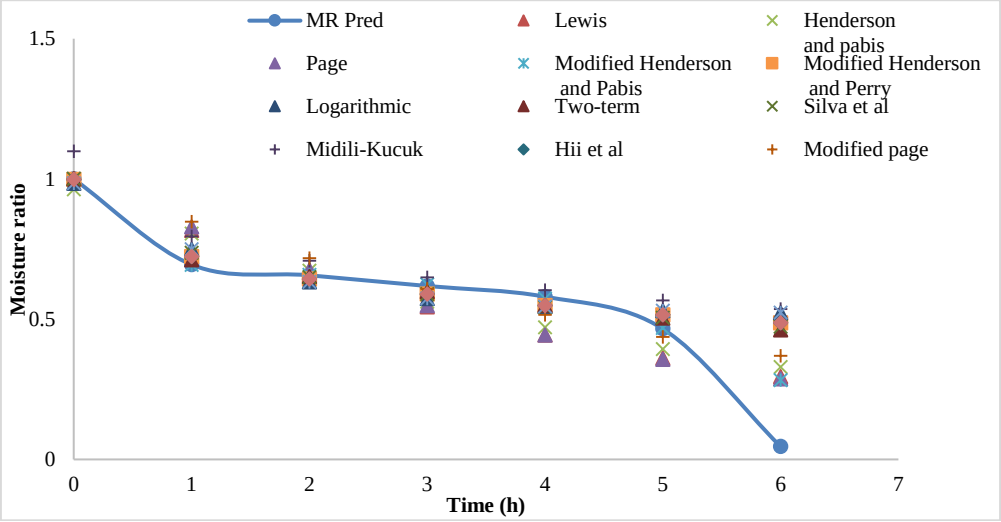


Figure 6: Drying model fitting (heat tray 1)

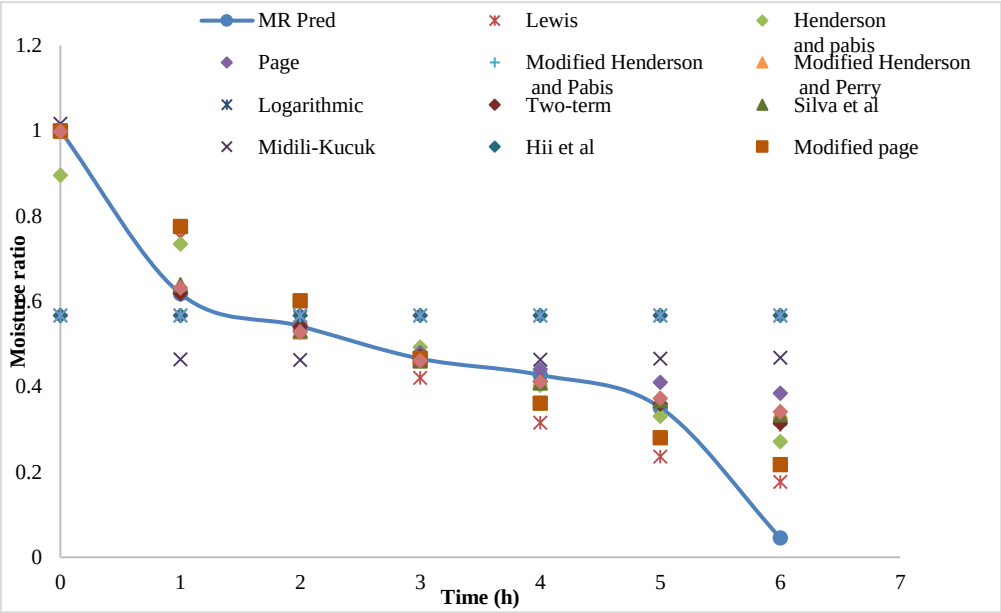


Figure 7: Drying model fitting (heat tray 2)

Table 7 presents the best-fit thin-layer drying models selected from thirteen evaluated models for fermented cocoa beans dried under three drying methods. Model selection was based on the highest R^2 and the lowest SSE and RMSE. The results indicate that no single model universally described the drying behavior across all conditions, which is consistent with findings reported in literature for agricultural products under varying drying conditions. For Solar drying, the Modified Henderson and Perry model ($R^2 = 0.9558$) and the Hii et al. model ($R^2 = 0.9831$) best described moisture loss in Trays 1 and 2, respectively. Under the Solar–Biomass method, the Hii et al. model ($R^2 = 0.9982$) and Modified Henderson and Pabis model ($R^2 = 0.9985$) provided the best fit, reflecting the more uniform and intense drying conditions produced by the combined heat sources. For Biomass-assisted drying, the Modified Henderson and Pabis ($R^2 = 0.9461$) and Page model ($R^2 = 0.9914$) performed best for Trays 1 and 2, respectively. Overall, the high R^2 values (>0.94) and low RMSE values across methods confirm the adequacy of the selected models in describing the thin-layer drying kinetics of fermented cocoa beans.

Table 7 Summary of Best-Fit thin-layer drying model constants, coefficients, and statistical indicators for fermented cocoa beans under three drying methods

Drying Method	Tray	Best-Fit Model	n	k	a	b	R^2	SSE	RMSE
Solar	1	Modified Henderson & Perry	1.1506	0.0997	0.9449	—	0.9558	0.0394	0.0551
Solar	2	Hii et al.	3.3092	$k_1 = 0.00042$; $k_2 = 1.6905$	0.6512	0.3467	0.9831	0.0119	0.0303
Solar–Biomass	1	Hii et al.	1.0450	$k_1 = 0.33868$; $k_2 = 0.3386$	0.1470	0.8489	0.9982	0.0014	0.0104
Solar–Biomass	2	Modified Henderson & Pabis	6.0041	10.1135	0.0841	0.9158	0.9985	0.0009	0.0083
Biomass	1	Modified Henderson & Pabis	6.5239	7.60×10^{-6}	0.4731	0.2615	0.9461	0.0398	0.0553
Biomass	2	Page	0.3797	0.4837	—	—	0.9914	0.0010	0.0087

Note: k = drying-rate constant; k_1 and k_2 = model-specific drying constants; n = drying exponent; a and b = model coefficients; R^2 = coefficient of determination; SSE = sum of squared errors; RMSE = root mean square error. Best-fit models were selected based on higher R^2 and lower SSE and RMSE values.

4. Discussion

The outcomes of this research show that the passive hybrid solar dryer was able to dry fermented cocoa beans under three different modes of operation; namely, solar drying, drying with solar and heat from briquettes and drying with heat from briquettes. It was observed that cocoa pod husk briquette was used as a supplementary heat source [32], thereby solving one of the most critical bottlenecks of PSDH which is a period when sun shine was low. This is especially crucial for cocoa beans that can suffer from quality degradation in case of inadequate or overly long drying periods.

The results obtained from the drying curves produced under the different heat regimes indicated that the drying environment affected the rate of drying of the cocoa beans, and that the position of the tray affected this rate of drying. In the case of solar only drying, the moisture ratio reduction was low and was due to fluctuations in ambient solar radiation [33]. This is consistent with the typical performance of a passive-drying system, as the amount of radiation incident and the temperature in the drying chamber fluctuates during the day. The drying air temperature and relative humidity determine the difference of vapor pressure between drying air and the product, so any variation of these parameters may cause disturbance in moisture migration, at first from inside the cocoa bean to the surface and then to the air [34].

When compared to solar-only and briquette-only drying, hybrid solar-briquette drying method yielded better performance of the model and generally higher coefficient of determination. It appears that the total heat input provided a better and more stable drying environment. Other practical scenarios include the fact that the heat source from the briquette was probably sufficient to keep burning outside daylight and was sufficient to offset the loss of heat in passive solar that is typically observed. This enabled moisture removal to proceed at a more consistent rate, reducing the risk of moisture rebound and under-drying. It is a significant benefit when drying cocoa beans continuously, where moisture reduction is essential to maintain the quality of the beans and to ward off the growth of fungal infection.

Drying behavior and model fit were also influenced by position of the trays. The values of R^2 for all the selected models were calculated by varying the values of output moisture contents and Tray 1 during the solar drying operations and were found to be nearly in the range of 0.9524–0.959 indicating that the most of the models describing moisture ratio data during the solar drying operation were good. When it comes to the solar-plus-heat condition, the R^2 range was even more elevated, starting with 0.9081 and ending at 0.9981. This wide spread indicates that some models were not as viable, while a few others were able to better describe the drying trend. The values of R^2 for tray 1 were in the range of 0.741–0.97106 under heat-source-only drying indicating high variation in the suitability of the models. This variation could be attributed to the different heat distribution, air flow and less contribution of radiant heat in comparison with the solar assisted drying.

The drying responses were slightly more variable for tray 2. The R^2 values ranged from 0.887–0.9831 under solar drying, from 0.374–0.9988 under hybrid drying, and from 0.5916–0.999144 under briquette-only drying. For some models, the R^2 values obtained were very low, indicating that some of these equations were not able to properly represent the moisture transfer pattern at this point on the tray. This can be due to non-uniform flow or stratification of temperature in the dryer. For passive systems, the upper and lower variables trays are frequently exposed to different dryers conditions temperature and convective, so that differences in the drying rate and overall drying kinetics occur.

Hybrid conditions were not suitable for all the thirteen models tested, but a few of them well-described the behavior of drying of cocoa beans especially under Hii et al. model, particularly in tray 2. For tray 1, the study has reported that from a sample of the expressions available, the modified Henderson and Pabis model or in particular for the computed tabulated values the Hii et al. or modified Henderson and Perry model, depending on the drying regime is the best fit. [31] observed high values of R^2 (0.9981) and (0.9558) for the solar and hybrid drying, respectively, for tray 1, while for tray 2 the respective R^2 values were 0.9988 and 0.9831. The above values show that the relationships between the predicted and experimental moisture ratios are very good.

The effectiveness of the Hii et al. model has been explained by its flexibility in having several constants that could account for the drying behaviour of cocoa beans which is very complex. Cocoa has seen complex drying behaviour; which cannot necessarily be well represented by simpler single-term models, like Newton and Henderson and Pabis [35]. Using the two exponential terms in the Hii

model enables the model to describe moisture migration in the different stages in which it occurs, such as the initial removal of loosely bound surface moisture and the slower movement of bound moisture through diffusion.

A well-known model used for drying of agricultural products was the Page model, which obtained mixed results in this study. It gave relatively good R^2 values, but did not consistently exceed the other heat and tray conditions. The Power-modified Exponential model is sometimes effective and applicable for the drying of cocoa beans but the drying process of cocoa beans in a hybrid dryer might have complexities that cannot be represented by this model [36]. In the same way, other models like Lewis (Newton), Logarithmic and Demir et al. were not as accurate in some other instances particularly if the drying condition was more variable.

More knowledge of the adequacy of a model is obtained from the SSE and RMSE. In general, a lower SSE and RMSE values result in more similarity between the predicted and experimental data. The SSE and RMSE values for the best performing models were reasonably small, which was consistent with the support of the R^2 results. The inconsistencies mentioned however do show in the tables as some of the RMSE values are much higher than expected for models with very high R^2 values. This could indicate that the data in the presentation may be incorrect or potentially contain computational, typographical or formatting errors. However, the general conclusion was again that the empirical models were inadequate and the models of Hii et al. and the modified Henderson were more suitable.

The drying rate behavior of cocoa beans in this study is likely characterized by a falling-rate period, which is common in most agricultural products [37]. During this period, moisture movement is primarily governed by internal diffusion rather than surface evaporation alone. For cocoa beans, the shell and cotyledon structure can impose resistance to moisture transfer, making the process strongly dependent on internal gradients. The gradual decline in drying rate with time would therefore be expected as the moisture content decreases. This behavior supports the suitability of thin-layer models that are capable of representing non-linear moisture ratio trends [38-41].

The use of cocoa pod husk briquettes as a supplementary energy source has practical significance beyond improved drying kinetics [42]. It enhances the sustainability of cocoa processing by utilizing an agricultural residue that is readily available in cocoa-producing regions. Instead of relying solely on firewood or fossil fuel-based heating, processors can convert cocoa waste into briquettes and use them to support continuous drying. This reduces waste disposal challenges, lowers environmental pressure on forest resources, and promotes circular resource utilization within the cocoa value chain.

From an engineering standpoint, the results suggest that passive hybrid solar dryers can be improved further by optimizing tray arrangement, airflow distribution, and chamber insulation to minimize differences between tray positions. Since tray 2 showed more variable model performance in some cases, a more uniform air circulation design may help achieve greater consistency in drying. Future studies may also examine bean quality attributes such as color, pH, free fatty acid content, flavor precursors, and microbial quality to complement the kinetic analysis.

The findings confirm that hybridization of a passive solar dryer with cocoa pod husk briquettes can significantly improve drying continuity and model predictability. The selected drying models, particularly the Hii et al. model, provide useful tools for describing moisture removal behavior and can support the design, simulation, and optimization of cocoa drying systems for small- and medium-scale processors.

5. Conclusions

This study evaluated the drying kinetics and characteristics of fermented cocoa beans in a passive hybrid solar dryer integrated with cocoa pod husk briquettes as an auxiliary heat source. The results confirm that the hybrid dryer is a viable technology for continuous cocoa drying under varying environmental conditions. By combining solar radiation during the day with briquette-generated heat during non-sunshine periods, the system overcame the major limitation of conventional passive solar dryers, namely interruption of the drying process. This continuous operation is essential for maintaining product quality and reducing postharvest losses.

The experimental drying data showed that drying behavior varied with tray position and heat source. In general, the hybrid solar-briquette mode produced better model fit and more stable drying characteristics than solar-only or briquette-only drying. Among the thirteen thin-layer models tested, the Hii et al. model gave the best overall performance, particularly for tray 2 and under hybrid drying conditions, with very high coefficient of determination values. For tray 1, the Hii et al. and modified Henderson-type models also performed strongly, indicating their suitability for representing cocoa bean drying behavior in this system.

The findings demonstrate that cocoa pod husk briquettes can serve as an effective and sustainable supplementary heat source for cocoa drying. This adds value to an agricultural waste material while supporting energy-efficient postharvest processing. The study contributes useful information for the design, optimization, and application of hybrid drying systems for cocoa. Future work should incorporate quality evaluation, energy analysis, and economic assessment to strengthen the case for large-scale adoption.

6. References

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