DEVELOPMENT OF A PASSIVE HYBRID SOLAR DRYER FOR COCOA BEAN

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ABSTRACT
A passive hybrid solar dryer was designed, fabricated and evaluated for cocoa bean drying, integrating solar and biomass energy sources to enhance drying efficiency under varying insolation conditions. The system comprises a solar collector, a drying chamber, and a biomass-fueled briquette chamber. The solar collector features a 3 mm thick acrylic cover, optimizing solar energy absorption. The drying chamber consists of two compartments for cocoa bean placement, while the lower chamber extends to accommodate an auxiliary heat source for uninterrupted drying. Briquettes derived from cocoa pod husks were utilized as an alternative energy source during periods of low or no solar radiation. Post-fabrication, a no-load test was conducted to assess baseline thermal performance, followed by experimental drying trials using fermented cocoa beans. The drying experiments were carried out between October and November, 2022, when the ambient temperature and relative humidity were within the ranges of 25.8-31.3℃and 58.7-89.0%, respectively. The cocoa beans achieved the desired moisture content in three days under solar drying alone, two days under hybrid drying, and within one day using only the biomass heat source. The average drying rates for solar, briquette and hybrid heat sources were 0.06, 0.3 and 0.35 kg/h, respectively while their temperature levels were within the ranges of 30.9-59.2, 30.4-56.4 and 29.5-61.5℃, respectively. However, it took a longer time for the heat to build up when solar radiation was used as the only heat source, resulting in the extended drying period. The developed hybrid system demonstrated a significant reduction in drying time, ensuring continuous and efficient drying, and thereby improving post-harvest processing of cocoa beans.

Keywords: Hybrid solar dryer, Cocoa bean, Briquette, Performance evaluation, Crop drying.

1. INTRODUCTION

Cocoa (*Theobroma cacao* L.) is an important agricultural commodity in West Africa, playing a crucial role in the economies of cocoa-producing nations such as Nigeria, Ghana, and Côte d'Ivoire (Dago and Pei, 2025). It serves as a primary raw material for the global chocolate industry and has numerous industrial applications in food processing, pharmaceuticals, and cosmetics (Bamboye *et al*., 2020). The post-harvest processing of cocoa beans is essential for maintaining quality, preventing spoilage, and enhancing its market value. Among these processes, fermentation and drying are two critical stages that directly influence the final quality of cocoa beans, particularly in terms of flavour, colour, and storage stability (Dina *et al*., 2015).

Drying plays a fundamental role in reducing the moisture content of cocoa beans to a safe level, thereby inhibiting microbial growth and enzymatic reactions that could lead to deterioration (Oyefeso *et al*., 2024). Proper drying enhances shelf life, improves handling and packaging efficiency, and ensures that cocoa beans meet industrial standards for further processing (Oyefeso and Raji, 2020a; Ogunlade *et al*., 2023). Traditionally, cocoa beans are dried under open sunlight, a method which has been reported to improve flavour and aroma (Santander *et* *al.*, 2025; Pita-Garcia *et al.*, 2025) although it is highly dependent on weather conditions and prone to contamination by dust, insects, and microbial pathogens. This necessitates the development of improved drying technologies that offer better control over drying parameters, reduce drying time, and enhance product quality.

With the increasing global demand for energy, the reliance on fossil fuels remains a major concern due to their significant contribution to greenhouse gas emissions and climate change (Ofori and Akoto, 2020; Lawal *et al*., 2023). The shift towards renewable energy sources, such as solar and biomass, has gained attention as a sustainable alternative to fossil fuel-based drying techniques. Solar drying systems have been widely adopted due to their energy efficiency, cost-effectiveness, and minimal environmental impact (Aremu *et al*., 2019). However, a key limitation of solar-dependent drying is its inconsistency, particularly in regions with fluctuating weather conditions or during night-time drying.

Biomass energy, derived from agricultural residues, presents an opportunity to complement solar drying and ensure continuous drying operations. Biomass offers several advantages, including wide availability, low environmental impact, and the potential to reduce reliance on deforestation-based fuel sources (Aremu and Ogunlade, 2014; Ofori and Akoto, 2020). However, the direct use of biomass as a heat source poses challenges, such as high moisture content, inefficient combustion, and smoke emissions (Wilaipon, 2007; Jaiyeoba *et al*., 2022). To overcome these drawbacks, briquetting technology has been introduced as a means of improving biomass fuel properties, enhancing energy density, and reducing emissions. Cocoa bean processing generates a substantial number of by-products, with cocoa pods accounting for approximately 70% of the total cocoa fruit mass (Vriesmann *et al*., 2011). The cocoa pod husks, which are often discarded as agricultural waste, can be effectively utilized as biomass feedstock for energy generation. The conversion of cocoa pod husks into briquettes provides an efficient and sustainable alternative to conventional biofuels, reducing waste accumulation while mitigating deforestation linked to firewood and charcoal production (Ofori and Teong-Lee, 2013).

The primary aim of this study was to develop and evaluate a passive hybrid solar dryer for cocoa beans, integrating solar energy with biomass briquettes derived from cocoa pod husks. The development of an efficient hybrid drying system for cocoa beans addresses multiple challenges in post-harvest processing. It offers a sustainable and cost-effective solution for smallholder farmers and industrial processors by optimizing drying conditions, minimizing post-harvest losses, and reducing dependence on fossil fuels. Additionally, the use of cocoa pod briquettes promotes a circular economy approach, converting agricultural waste into a valuable energy source while supporting environmental sustainability. This study contributes to advancing renewable energy applications in agriculture, aligning with global efforts to promote sustainable food production, carbon footprint reduction, and climate resilience in tropical agricultural systems.

2. MATERIALS AND METHODS

In the passive hybrid solar dryer, the main components were the transparent cover, solar collector, drying chamber, drying racks, air inlet and outlet vents, insulation, supporting framework and the alternative energy source. The transparent cover (3 mm thick transparent acrylic sheet) was used cover the dryer in order to trap the solar energy. It allows the short wavelength solar radiation to pass through it and traps it by converting them to long wavelength thereby enhancing heat build-up) in the drying chamber. The solar collector consists a black metallic heat absorber which was integrated with the floor of the drying chamber and slightly tilted to ensure better insolation from the sun. The drying chamber was constructed with a plywood, covered with an aluminum foil paper which helps to reflect solar radiation and internal heat back into the drying chamber, thereby, reducing heat loss. The drying chamber was where the products to be dried were placed and actual moisture removal took place. The drying trays on which the products were placed during drying were made of wire mesh to achieve the minimum resistance to airflow. The product was put in an aluminum tray, which was placed on the wire mesh. At the lower part of the dryer, there was a chamber made for an additional heat source. The alternative heat energy source used in this study was briquettes which made from cocoa pods. The supporting framework holds all the other components in place and ensure the stability of the assembly. Figure 1 shows orthographic view of the hybrid solar dryer, while Figure 2 shows the isometric representation and the fabricated hybrid solar dryer.

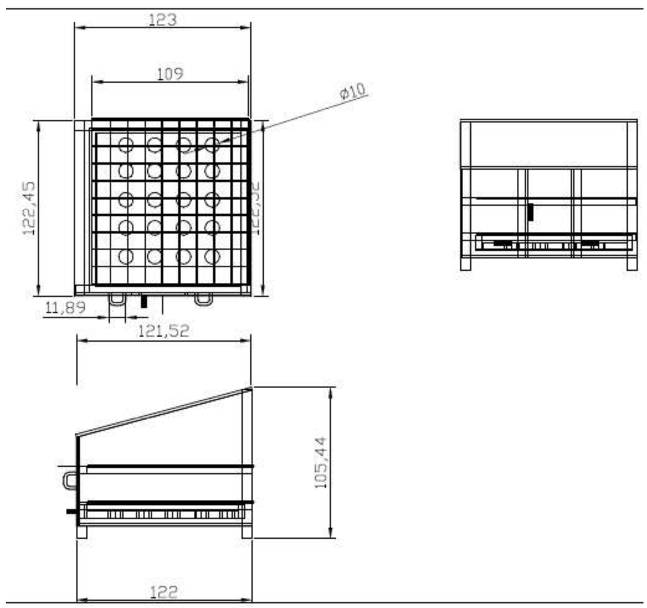
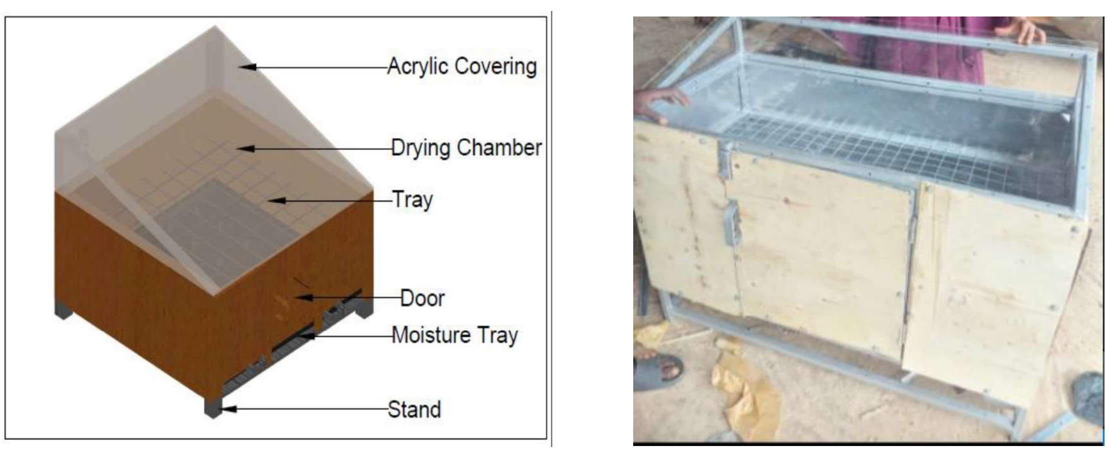


Figure 1. Orthographic view of the hybrid dryer (all units in cm)



(a) (b)

Figure 2. (a) Isometric representation and (b) the fabricated hybrid solar dryer

2.1 Design Calculations

2.1.1 Determination of tray size

The average harvest of a small scale cocoa farmer within one year (365 days) was estimated to be between 600 and 800 kg. Therefore, 800 kg was used in the design of the capacity of the hybrid solar dryer.

The average harvest per day = $\frac{800}{365}$ = 2.19 kg/day ≈ 2.2 kg/day.

The dryer was designed to house 2 trays. Therefore, the mass of cocoa on each tray will be 1.1 kg/tray.

Since the average bulk density of cocoa is 593 kg/m^3 (Bart-Plange *et al.*, 2012), it indicates that 593 kg of fresh cocoa occupies 1m^3 by volume. Then, 2.2 kg of fresh cocoa will occupy 0.00371 m^3, which is equivalent to an average volume of 3,710 cm^3.

2.1.2 Determination of the quantity of moisture to be removed

According to Lasisi (2014), a safe moisture level of below 8.0% (wet basis) is recommended for cocoa beans for improved storability. To calculate the quantity of water to be removed to attain a safe moisture content of 7.5% for cocoa beans, the following data were used:

The initial moisture content of cocoa, m_I, according to oven drying = 52.2% (wet basis)
The desired final moisture of product, m_f = 7.5% (wet basis) (Ndukwu *et al.*, 2010)
Total mass of wet product to be dried, m_p = 2.2 kg

Amount of water to be removed (m_w) was determined to be 1.063 kg according to Equation (1).

$$m_w = \frac{(m_i - m_f)m_p}{100 - m_f} \tag{1}$$

2.1.3 Determination of moisture pick up rate in the product

The pick-up rate was calculated as the average quantity of moisture picked up per time. The average daylight in Ibadan for October is about 12 hours/day, out of which the sunlight hour is about 6 hours/day (Adewumi and Adelekan, 2015). Assuming that the drying process will be completed in 3 days, then the drying time of the product (T_d) was estimated to be 18 hours.

The average quantity of moisture picked up per hour was calculated to be 0.059 kg/hr according to Equation (2).

$$V_{ap} = \frac{m_w}{T_d} \tag{2}$$

2.1.4 Determination of the quantity of heat needed to remove moisture

The quantity of heat that will be required to evaporate the water from the product was calculated to be 351.70 kJ using Equation (3).

$$Q = m_w \times h_{fg} \tag{3}$$

where,

Q is the energy required to remove moisture (kJ)
m_w is the mass of water to be removed (kg)

h_{fg} is the latent heat of evaporation of water (kJ/kg).

2.2 System Drying Efficiency

The system drying efficiency was calculated as the ratio of the energy required to evaporate the moisture to the heat supplied to the dryer according to Equation 4. Figure 3 shows the cocoa beans before and after drying using the developed hybrid solar dryer, while the cocoa beans during drying are shown in Figure 4.

$$\eta_d = \frac{m_w \times h_{fg}}{A \times I_c \times T} \tag{4}$$

where,

η_d is the system drying efficiency (%)
A is the area of the solar collector (m^2)
I_c is the insolation on the collector (W/m^2)
T is the drying time (s)

(a) (b)

Figure 3. (a) The cocoa beans before drying and (b) after drying with the developed hybrid solar dryer

Figure 4. Cocoa beans during the drying experiment using the developed dryer

2.3 Evaluation of the Dryer

2.3.1 No-load evaluation

No-load evaluation of the hybrid solar dryer was carried by taking measurements of the solar radiation, ambient and the drying chamber conditions (temperature and relative humidity). The experimental data from the climatic conditions were plotted against time. The observations and recordings were done from 10.00 am to 5.00 pm at an interval of 1 hour.

2.3.2 Drying of cocoa beans

Fresh cocoa pods used in this study were acquired from Oko town in Oyo State, Nigeria. The fresh cocoa beans were separated from the cocoa pods after they were cleaned and cut open. The cocoa beans were fermented in a fermentation bag for a period of 5 days (Afoakwa *et al*., 2008). The fermented coca beans were weighed and spread thinly on the drying tray and placed in the drying chamber. Before the commencement of the drying experiments, data loggers were placed in the solar dryer to monitor the temperature and relative humidity at 30 minutes' interval. A no-load pre-heating period of one hour was done before the commencement of the experiment to allow for equilibration of the temperature within the hybrid solar dryer. The turning of the cocoa beans in the drying tray was done after every one hour for uniform drying. The experiment was terminated when it was observed that the bean had fully dried to the desired moisture content. The drying experiments were carried out between 9:00 am and 5:00 pm. By 5pm when the sun has set, the cocoa pod briquettes which were used as the alternative energy source were ignited for the drying process to continue all through the night. The weight of the cocoa beans were weighed before the commencement of the drying experiments and at an hour interval during the drying experiments, which continued until the moisture content reached about 7.5% (wet basis).

2.4 Drying Behaviour of the Cocoa Bean

The variations in the ambient and drying air temperature and relative humidity levels were plotted against the drying time. Variations in the mass of the samples being dried with drying time and the average drying rates were also determined for the drying experiments. Drying rate curves such as variation in moisture content of the samples were plotted against the drying time to describe the drying behaviour of the cocoa beans.

2.5 Statistical Analysis

Data loggers were used to monitor the ambient and drying chamber air conditions (temperature and relative humidity) throughout the period of the experiments. The experimental data obtained from the study were subjected to descriptive statistics and regression analysis using data analysis tools in Microsoft Excel (2016 Version).

3. RESULTS AND DISCUSSION

The drying experiments were carried out between October and November, 2022. The intensity of the ultraviolent (UV) radiation ranged from 50 to 3,069 $\mu W/cm^2$, while the solar radiation during the period ranged between 10.42 and 468.9 W/m^2. The ambient temperature and relative humidity also ranged from 25.77 to 31.32℃ and 64.2 to 84.4%, respectively, during the period of the drying experiments.

3.1 Temperature Variation against Time at No-load Test

Figure 5 shows the observed temperature variations in the dryer when solar radiation alone was used as the heat source for the no-load performance evaluation. The highest temperature recorded on trays 1 and 2 were 57.2 and 54.1℃, respectively. In the hybrid drying (which involves the combination of solar and briquette as the heat source), the maximum temperatures recorded were 57.2 and 57.8℃ on trays 1 and 2, respectively as shown in Figure 6. Figure 7 shows the temperature variation for briquette heat source alone with peak temperatures of 54.3 and 57.8℃ on trays 1 and 2, respectively. From the results obtained during the no-load test, it was observed that the air temperature levels in the drying chamber of the dryer (on both trays 1 and tray) were significantly higher than the ambient temperature levels throughout the period of the experiments. Thus, it can be concluded, that the dryer raised the temperature levels significantly above than those of the ambient conditions.

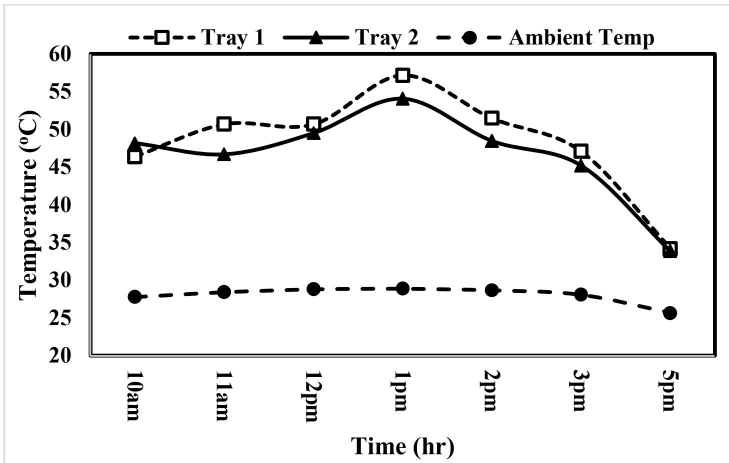


Figure 5. No load temperature profile when using solar alone as the heat source

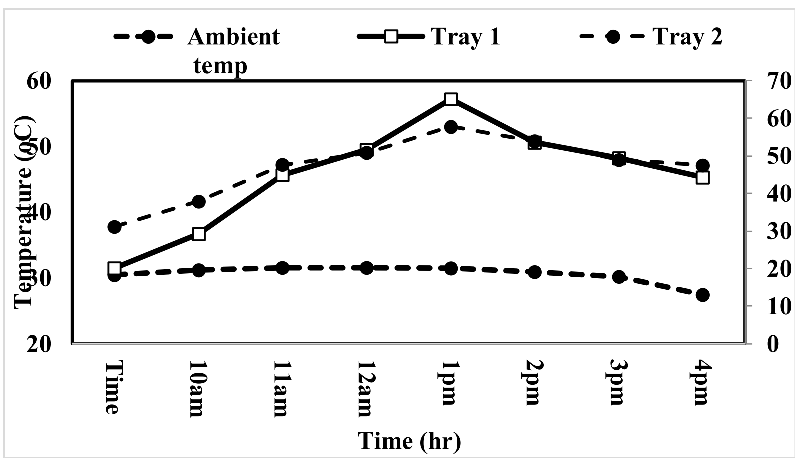


Figure 6. No-load temperature profile when using solar and briquette as the heat **source**

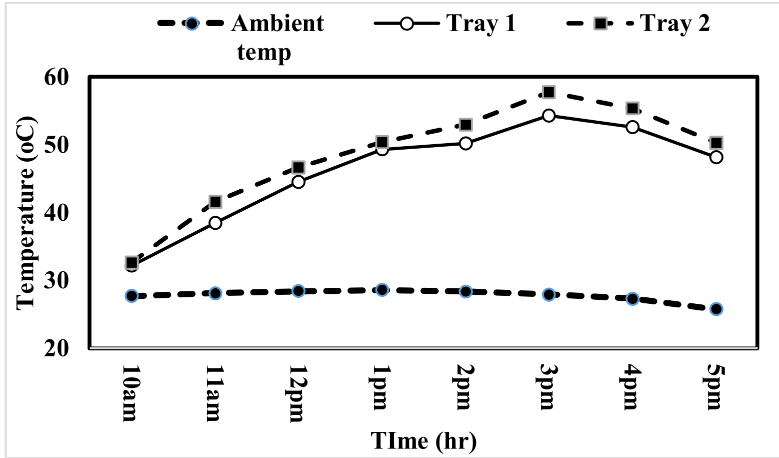


Figure 7. No-load temperature profile when using briquette as the heat source

The no-load test results showed that there was a significant increase in the temperature within the drying chamber on both trays 1 and 2 compared with the ambient temperature throughout the experiments. The temperature variation recorded from 10:00 am to 5:00 pm demonstrated the effectiveness of solar radiation and biomass-based heat sources in raising the internal drying chamber temperature. The highest temperatures observed in trays 1 and 2 under solar drying alone were 57.2 and 54.1°C, respectively, indicating that the solar collector effectively harnessed solar energy to heat the drying chamber. However, variations in recorded temperatures between trays suggest non-uniform heat distribution, possibly due to differences in air circulation and solar intensity at different times of the day.

When the hybrid drying mode (combination of solar and briquette as the heat source) was applied, the temperature inside the drying chamber increased further, with peak values of 57.2°C in tray 1 and 57.8°C in Tray 2. This demonstrates that the integration of a biomass heat source enhances thermal efficiency and provides a more stable and consistent temperature within the dryer. Compared to solar drying alone, hybrid drying reduces temperature fluctuations caused by varying solar intensity, ensuring a more controlled drying environment. Similarly, in the biomass-only mode, Tray 1 and Tray 2 recorded peak temperatures of 54.3°C and 57.8°C, respectively. These results confirm that the briquette-fuelled heat source is capable of maintaining sufficiently high temperatures for drying even in the absence of solar radiation.

Overall, the no-load test confirmed that the developed hybrid solar dryer effectively raised the drying chamber temperature above ambient levels, a crucial factor in improving drying efficiency (Santander *et al.*, 2025). The hybrid mode yielded the most stable and elevated temperature conditions, highlighting its potential for continuous drying regardless of solar availability. Additionally, the performance of the briquette-fuelled heat source suggests that agricultural waste, such as cocoa pod husks, can serve as an effective alternative energy source for drying applications. These findings emphasize the importance of integrating hybrid energy sources to enhance the reliability and efficiency of post-harvest processing systems.

4.2 Temperature Profile during the Drying of the Cocoa Bean

The average initial moisture content of the fermented cocoa beans at the point of commencement of the experiment was 52.4-60 % for all the samples. The introduction of the cocoa bean in the dryer was followed by temperature against time observations at an interval of 1 hour. Using energy source obtained from solar radiation only, Figure 6 shows the temperature recordings in tray 1 and 2 were at its peak at 56.0 and 50.9ºC, respectively. The recommended final moisture content for dried cocoa bean should be less than 8.0% to avoid growth of micro-organisms and for good storage (Lasisi, 2014). From the results, it was observed that it took the fabricated dryer using only solar radiation as its energy source took 12 hours to dry the cocoa bean. This was a longer period of drying the cocoa beans compared to using hybrid or briquette heat source alone.

It took approximately 7 hours to reduce the bean moisture content to it safe level when using solar radiation and heat source as source of energy of heating the drying air. The temperature observed for trays 1 and 2 were 61.5 and 59.4ºC, respectively. Using the heat source as a form of energy source the highest temperature recordings in trays 1 and 2 were 56.3 and 56.4ºC and it took about 6 hours to reduce the moisture content to below 8%. The drying process took place in the falling rate period throughout the experiments where the drying ratio decreases continuously with the reduction in moisture content and the increment in drying time.

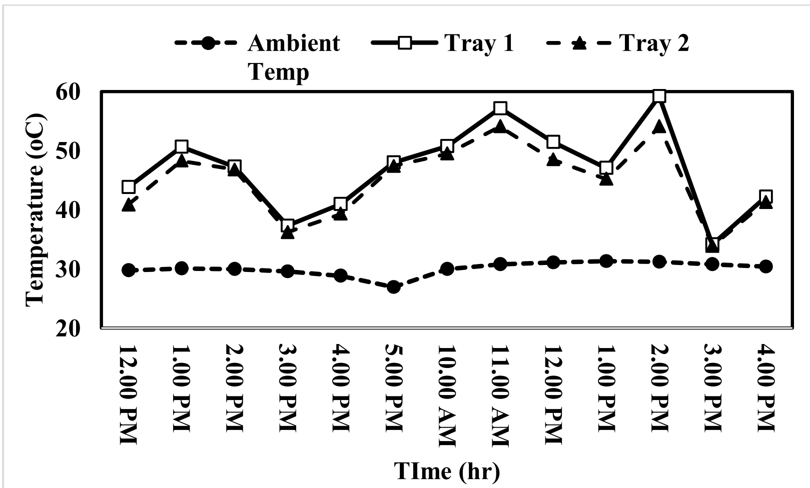


Figure 8. Temperature profile when using solar alone as heat source

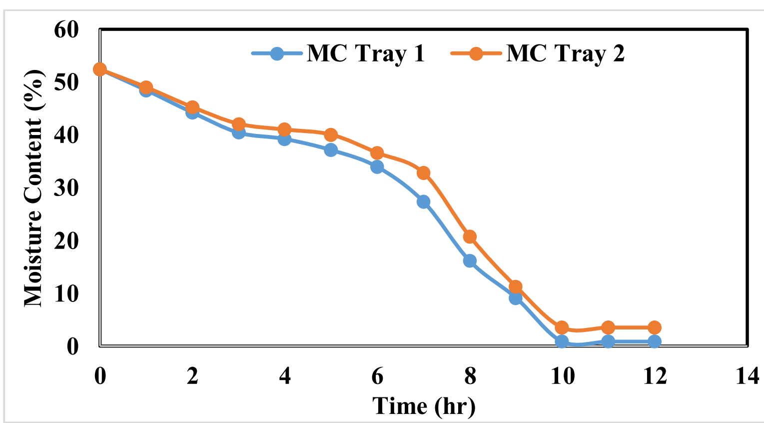


Figure 9. Drying curve for solar alone as heat source

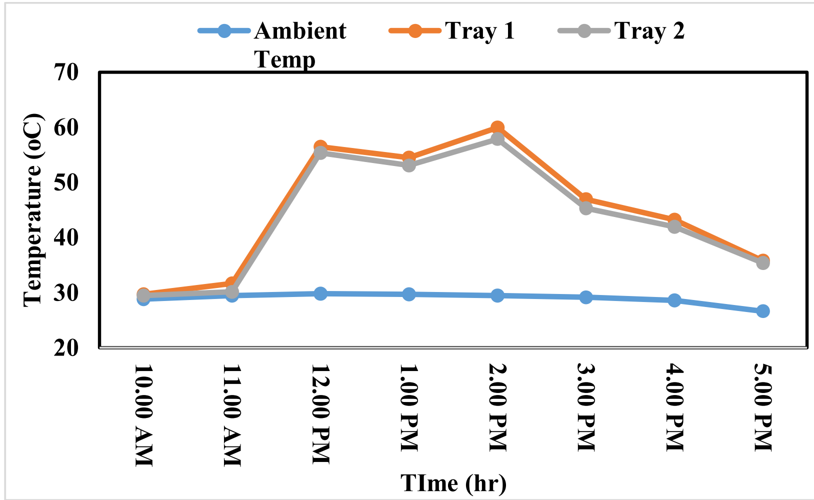


Figure 10. Temperature profile when using solar and briquettes as heat sources

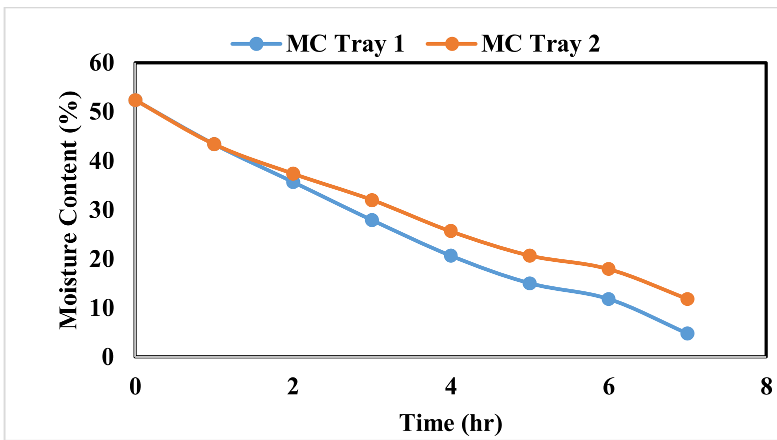


Figure 11. Drying curve for solar and briquette as heat sources

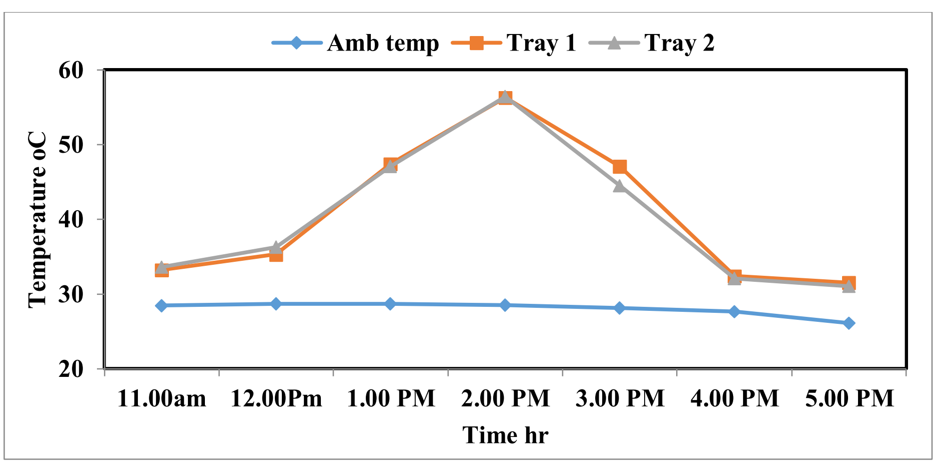


Figure 12. Temperature profile when using briquette alone as the heat source

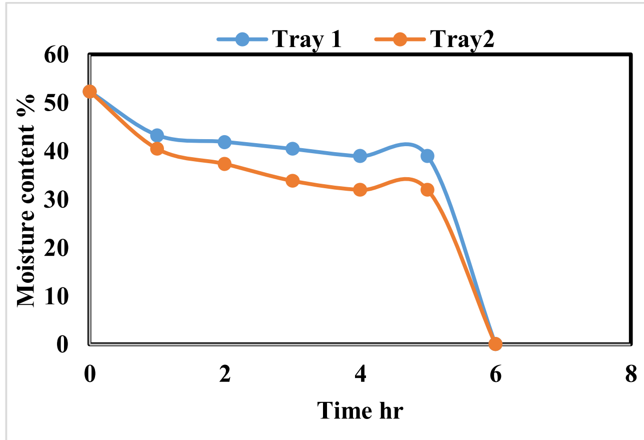


Figure 13. Drying curve when using briquette alone as the heat source

The average drying rates for solar, briquette and hybrid heat sources were 0.06, 0.3 and 0.35 kg/h, respectively while their temperature levels were within the ranges of 30.9-59.2, 30.4-56.4 and 29.5-61.5℃, respectively.

The drying curves for the cocoa beans showing the moisture content profile during the drying experiments (Figures 9, 11 and 13) showed that the drying behaviour was predominantly in the falling rate regimes, similar to the findings of Oyefeso and Raji (2020a, b). However, the drying curve for the hybrid dryer combining both solar and briquette as energy sources was steeper than the others, indicating a more rapid moisture removal due to higher drying temperature attained. Some constant rate drying were also observed in the drying curves for solar radiation and briquette used individually as single heat sources, which may be attributes to the high moisture content of the cocoa beans at the initial phase of drying and the relatively lower drying temperatures observed for the individual heat sources.

The drying experiments conducted after introducing fermented cocoa beans into the dryer provided essential data on the drying efficiency of different energy sources. When using only solar radiation as the heat source, the peak temperatures recorded were 56.0°C in tray 1 and 50.9°C in tray 2, with a gradual decline in moisture content over time. The cocoa beans were turned hourly to ensure uniform drying, and the drying process was completed when the moisture content reached 4.8% (Tray 1) and 6.6% (Tray 2). Given that the recommended moisture content for safe cocoa bean storage is below 8%, this confirms the effectiveness of solar drying in achieving the desired moisture reduction. However, the drying time was relatively long, taking 12 hours to reach the safe moisture level, which highlights the limitations of relying solely on solar radiation, especially in regions with inconsistent sunlight exposure.

In contrast, the hybrid drying system, which combined solar radiation with an additional heat source (briquette combustion), demonstrated a significant improvement in drying efficiency. With peak temperatures of 61.5°C in Tray 1 and 59.4°C in Tray 2, the drying time was reduced to approximately 7 hours. This suggests that supplementing solar radiation with biomass-derived heat enhances heat transfer within the drying chamber, leading to faster moisture evaporation and shorter drying durations. The consistent temperature levels recorded in both trays indicate a more uniform drying process compared to solar drying alone. The temperature levels generated in the hybrid dryer were within the levels recommended for cocoa beans drying (below 70℃). Furthermore, the results validate the effectiveness of hybrid drying systems in improving post-harvest processing, particularly in reducing drying time while maintaining the desired final moisture content for proper storage and quality preservation.

When using only the heat source (briquette combustion) as the drying energy, the maximum temperatures recorded were 56.3°C in Tray 1 and 56.4°C in Tray 2, and the drying duration was further reduced to 6 hours. This demonstrates that biomass energy, when properly utilized, can serve as a reliable alternative to solar energy, ensuring continuous drying even in the absence of sunlight. The drying process followed a falling rate period, where the drying rate decreased as the moisture content reduced over time. This trend aligns with the typical drying behaviour of biological materials, where moisture diffusion becomes the limiting factor as the drying progresses. These results emphasize the importance of integrating alternative heat sources such as briquettes into drying systems to enhance efficiency, reduce dependency on weather conditions, and ensure consistent drying performance for post-harvest agricultural products.

4. CONCLUSIONS

A passive hybrid solar dryer for cocoa bean drying was designed, fabricated and evaluated. The dryer integrates solar energy with biomass heat derived from cocoa pod husks. The temperature levels generated in the hybrid dryer were within the levels recommended for cocoa beans drying. Experimental results demonstrated that the hybrid system significantly enhanced the drying efficiency compared to traditional solar drying. Under solar-only conditions, the cocoa beans reached the recommended safe moisture content in 12 hours, whereas the hybrid system reduced this drying time to 7 hours by supplementing solar radiation with biomass heat. When using only the biomass heat source, the drying process was further expedited to 6 hours. The observed temperature profiles indicated that the dryer maintained internal temperatures well above ambient levels, facilitating a consistent and uniform drying process. The drying behaviour of the cocoa beans was predominantly in the falling rate regime although some constant rate drying were observed for solar radiation and briquette used individually as single heat sources at the initial phase of drying. The integration of solar and biomass energy sources did not only enhance operational reliability under variable weather conditions but also supports environmental sustainability. Future work should focus on further optimizing the dryer design, exploring scale-up potential, and incorporating advanced monitoring systems to refine the drying kinetics and maximize energy utilization.

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