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DEVELOPMENT OF A HYBRID COCOA SEED DRYER USING SOLAR ENERGY AND HOT AIR

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Abstract: The drying platform, drying chamber, heating duct, chimney, and roof cover were all part of the hybrid cocoa dryer designed and constructed in this study to, investigate the drying behavior of cocoa seeds using a controlled drying process, with an initial seed mass of 25.0 kg and an initial moisture content of 55% (dry basis). The drying process was conducted over a period of 7h, during which key parameters, including mass, temperature, and moisture content, were recorded hourly across three replicates. The average temperature ranged between 50°C and 60°C. Results showed a consistent decrease in both mass and moisture content over time, with the final average mass reaching 5.17 kg and moisture content dropping to 10.27%. The drying rate, determined by the change in the moisture content over time, was the highest during the initial stages and gradually declined as drying progressed. The data demonstrate typical drying kinetics of agricultural products, where rapid moisture loss occurs initially followed by a slower drying rate in later stages. These findings are significant for optimizing cocoa drying processes to ensure product quality, reduce postharvest losses, and improve energy efficiency.

Keywords: Development, Hybrid, Cocoa seed dryer, Solar Energy, Hot Air.

1. INTRODUCTION

Cocoa (Theobroma cacao) is a vital cash crop and a significant source of income for millions of farmers in tropical regions, particularly in West Africa, Latin America, and Southeast Asia. Its seeds, commonly known as cocoa beans, are the primary raw material for the global chocolate industry. The postharvest processing of cocoa beans—including fermentation and drying—is essential in determining the final flavor, quality, and market value of the beans (Afoakwa et al., 2008). Among these processes, drying plays a crucial role in reducing the moisture content of fermented beans from around 60% to a safe storage level of about 6%–8%, thereby preventing microbial growth, reducing the risk of mold contamination, and preserving quality during storage and transportation (Arinola et al., 2019). Traditionally, cocoa farmers rely on open-sun drying due to its low operational cost and simplicity. However, sun drying is highly weather-dependent and, time-consuming and exposes the beans to dust, insects, and animal droppings (Kyi et al., 2001). These limitations often result in inconsistent drying and poor quality of beans. Mechanical drying using hot air offers better control over temperature and drying time, leading to more uniform drying. However, it is energy-intensive and may not be economically viable for smallholder farmers in off-grid rural areas (Amponsah et al., 2014).

The integration of solar (sunshine) drying with controlled hot air systems has emerged as a promising solution to overcome these challenges. A hybrid dryer that utilizes both solar energy and hot air can provide a more sustainable and energy-efficient method of drying cocoa beans, ensuring consistency, reducing drying time, and improving bean quality. Such systems aim to harness renewable energy while maintaining reliability during periods of low sunlight, offering a balance between cost-effectiveness and performance (Forson et al., 2007). This study focuses on the development of a Cocoa Seeds Hot Air and Sunshine Dryer to, design a hybrid drying system that addresses the limitations of traditional and mechanical drying methods. The project seeks to improve post-harvest processing efficiency, reduce post-harvest losses, and ultimately enhance cocoa farmers' livelihoods through better quality cocoa production.

The western part of the country is said to be the highest producer of cocoa in Nigeria, with Ekiti, Ondo, Oyo, Osun, and Ogun accounting for about 80% of the country's cocoa production. In addition, states like Edo and Cross-river are actively involved in crop production. Ondo State is the largest cocoa producer in Nigeria. Ondo state produces approximately 80,000 tons of cocoa every year. Ondo State is in the humid rain forest belt of Nigeria, which favors cocoa cultivation. The major cocoa-producing towns in Ondo state are Ondo, Ile-oluji, Idanre, Akure, Ogbese, Odigbo, and Owo. There are many cocoa processing companies in Ondo state due to the large number of cocoa farmers in the state. End products from cocoa beans, especially chocolate and beverages, are considered basic food in many countries, and the quality of these end products is a function of how they are processed (Ndukwu et al. 2010). Fermentation and drying constitute key farm-based unit operations that strongly influence the final quality of cocoa beans and their subsequent products. Recent studies on the drying process and its effects on quality point to three principal issues—method, temperature, and drying duration (Castellanos et al. 2018). Primary processing of cocoa seeds is time-consuming and hard work from the farmer's point of view. Farmers are weary of the problem of excessive drying and quick drying of cocoa beans by heated dryers; excessive drying will not be economical in terms of amount of money received by farmers because cocoa is sold by weight. It will also increase the energy costs, while quick drying will prevent the completion of the chemical processes that started during fermentation because curing is important in cocoa drying because, acetic acid is mainly produced by oxidation of ethanol in the presence of oxygen by acetic acid bacteria. During drying, this acid is evaporated along with the moisture removal process due to its volatile nature. However, the lactic acid contained inside cannot be evaporated off because it is a less volatile compound; therefore, curing solves this problem (Ndukwu et al., 2010). In an attempt to optimize the drying process and obtain optimal cocoa seed quality with minimal cost, several modifications in the drying parameters were performed (Banboye et al., 2020). Any drying system that minimizes exposure of food to light (ultraviolet (UV)), oxidation, and heat will help conserve critical bioactive compounds required for high produce quality (Ahmed et al., 2013). During drying, the water activity of food is reduced due to a reduction in its moisture content through the application of heat (Fernandes et al., 2011). Cocoa beans are considered dry and suitable for marketing if their moisture content has been reduced to between 5% and 8% (wet base) (CAC/RCP, 2013). Some common methods of drying cocoa seeds include open sun drying, solar drying, oven drying, microwave drying, and freeze drying. However, limited studies have been reported on the use of hot air and firewood as fuel for cocoa seed drying.

Some poorly informed farmers dry their cocoa beans on bare ground (exposing them to contamination by stones, soil, and surface organisms) and some on tarred road sides (exposing them to contamination by carcinogenic compounds) (Tardzenyuy, 2020). Method is not practically feasible during periods of heavy rain and high humidity (Dzelagha, 2020). In recent years, studies have been conducted and reported on the drying of cocoa beans using solar and artificial drying methods in comparison with traditional open sun drying (Ndukwu et al., 2010). However, studies on the use of firewood for cocoa drying are limited.

1.1 Aim and Objectives of the Research

i. This project aimed to design, construct, and test a hybrid cocoa seed drying system that integrates hot air drying and solar (sunshine) drying methods. The primary objective of this study was to enhance the drying efficiency, ensure quality retention of cocoa beans, and reduce dependence on unpredictable weather typical in tropical regions.

The specific objectives are to:

ii. design an efficient hot air and sunshine dryer for cocoa seeds,
iii. estimate the construction cost of a prototype hot air and sunshine dryer using locally sourced materials,
iv. constructing a prototype cocoa hot air and sunshine dryer and;
v. discover the principles in the design, construction, and maintenance of hot air and sunshine dryers for cocoa seeds

2. MATERIALS AND METHODS

The air temperature is a measure of the average kinetic energy of air molecules. When air is heated, molecules gain kinetic energy and move faster, causing the air temperature to rise. The temperature is influenced by its surroundings and the energy exchanges that occur with those surroundings. Conversely, air can release heat to cooler surfaces, leading to a decrease in air temperature and an increase in surface temperature.

2.1 Design Equations

The total energy required for the drying of cocoa can be calculated using the following equation; Seveda (2012) and Komolafe et al. (2014)

$$Q = Md \times CC \text{ X } (T_1 - T_2) + \text{M x Cp x } (T_1 - T_2) + \text{Mw x L} \qquad (1)$$

Here, Q is the total energy required for drying the beans (kJ), Md is the mass of bone dry beans in kg , cc is the specific heat of beans in $kJkg^{-10}C^{-1}$, T_2 is the temperature inside the drying chamber in ^0C, T_1 is the ambient air temperature in ^0C, M is the mass of the initial water content in kg, Cp is the specific heat capacity of water in kJ $kg^{-10}C^{-1}$, Mw is the mass of water to be removed in kg, and L is the latent heat of vaporization of water in kJkg. The total amount of heat needed for drying will be supplied by burned wood, and this can be calculated using the following equation:

$$QT = Mwt\text{Sp CW} \qquad (2)$$

Where QT is the total amount of heat in (J), Mwt is the total mass of wood in kg, and SpCw is the specific calorific value of wood in MJ/kg. The heat required to evaluate the moisture and keep the beans at the dryer temperature can be calculated based on the principles of heat transfer according to the equation by Karlekar et al. (1982)

$$E = mcccdT + \text{MWL} \qquad (3)$$

Where E is the heat required to evaporate the moisture, mc is the mass of cocoa beans, cc is the specific heat of beans kJ $kg^{-10}C^{-1}$, Mw is the mass of water to be removed in kg, L is the latent heat of vaporization of water $kJkg^{-1}$ and dT is the change in temperature in ^0C.While the total rate of heat transfer to the drying cocoa beans will be a combination of conductive, convective, and radiative. The entire development, comprising the design, construction, and assembly of various parts, involves the following:

i. drying platform
ii. drying chamber
iii. heating duct

iv. air inlet holes
v. chimney
vi. roof cover

2.1.1 Design analysis and calculations

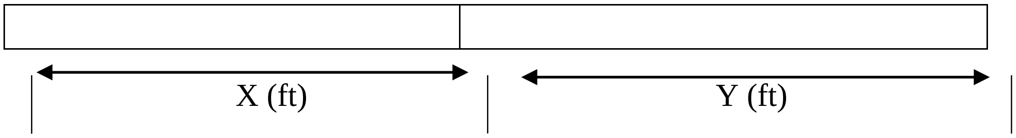
The following are various dryer sizes;

Area = length (L) x Width (W)

Volume = length (L) x Width (W) x Height (H)

2.1.1 Drying Platform

This refers to the space of the dryer used to spread the wet cocoa seeds, which will be made of stainless steel.



Where;
X = width of stainless steel (ft)
Y = length of stainless steel (ft)
Therefore;

$$\text{Total area (T)} = X*Y\ (ft^2) \tag{4}$$

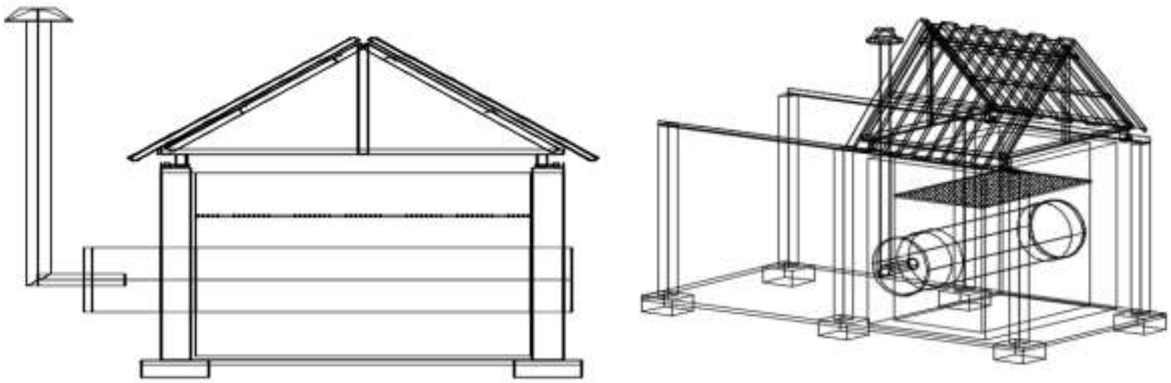


Figure 1: Orthographic view

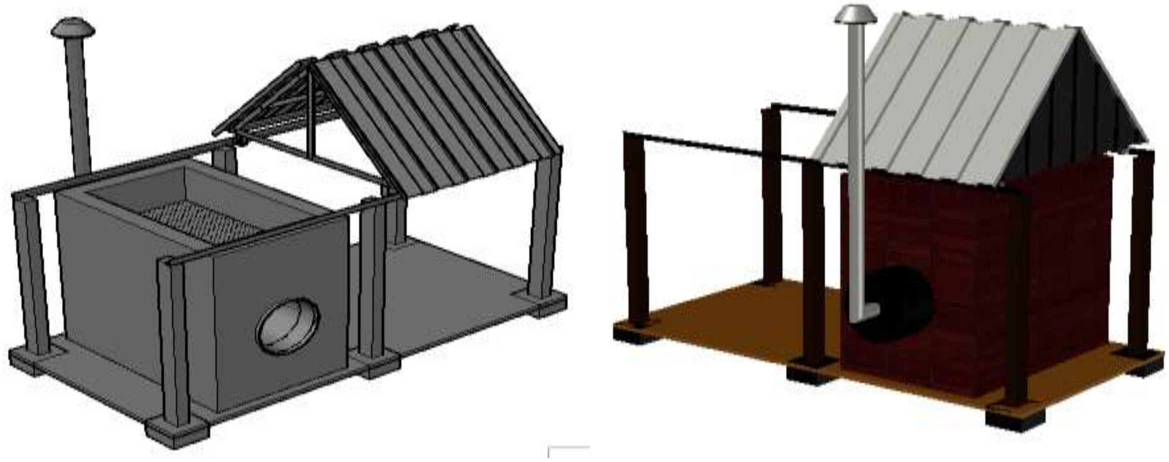


Figure 2: Isometric view

2.2 Material Selection

Involves the choice of materials to be used in the construction of the project. Material selection is also based on the following factors of material selection criteria;

Table 1 shows, the various components of the design, the materials used, and the selection criteria for the materials

Table 1: Selection of materials

COMPONENTS	FUNCTION/DESCRIPTION	MATERIAL SELECTED	CRITERIA FOR THE SELECTION
Drying Platform	A perforated flat steel platform was used to spread out the cocoa beans for, easy access to hot air from the drying chamber and direct sunlight. The platform can serve as a temporary storage for produce before and after drying.	Stainless steel	High heat conductor, does not easily corrode, and is food friendly
Drying Chamber	Red bricks encircle the area to prevent heat loss during drying. The drying chamber houses the hot air generated as a result of convection and radiation from the heating duct to supply it.	Fired bricks	Readily available and can retain heat
Heating duct	A cylindrical chamber surrounded by a drying chamber, where heat is produced by burning fuel such as wood or charcoal. One end is constructed to loop with the smokestack, while the other end opens for fuel loading.	Galvanized Steel	Malleable, ductile, and available
Chimney	A steel ventilation structure to separate hot, poisonous exhaust fumes or smoke from the heating duct.	Galvanized Steel	Malleable, ductile, and available
Roof cover	A movable roof structure made of iron and aluminum sheets that encloses the drying platform. It is often opened during solar drying and can be closed or opened based on user preference and weather conditions.	Iron and aluminum sheets	Readily available and relatively inexpensive

2.2.1 Operating Temperature

Temperature is often the first and sometimes the only data point given upon which material selection is based However, one cannot successfully choose a material based on temperature alone. Nevertheless, a simple guide to material selection is an estimate of the maximum temperature at which a given material might have useful long-term engineering properties. (Akinfaloye, 2021).

i. Thermal Stability
ii. Suitability of the material for the intended purpose

iii. Strength.
iv. Cost and availability of the materials
v. Oxidation

2.3 Evaluation Criteria

a. Design Effectiveness
b. Drying Efficiency
c. Energy Consumption
d. Product Quality
e. Cost Efficiency
f. Operational Feasibility

Design Effectiveness: The hybrid dryer was designed with a dual-chamber system, allowing simultaneous or alternate use of solar and hot air mechanisms. The structure incorporated transparent covers for solar absorption and an insulated compartment for integration of electric/hot air. The design proved to be both innovative and practical for rural or semi-urban deployment.

Drying Efficiency: The dryer significantly reduced the total drying time of cocoa seeds from 6–7 days (sun drying only) to approximately 36–48h depending on ambient conditions and batch size. This improvement supports better postharvest processing and throughput.

Energy Consumption: The dryer consumed a modest amount of solar energy when operating in hot air mode, which can be offset by integrating renewable sources like solar panels. The system also efficiently used passive solar energy during daylight hours.

Product Quality: Beans dried with the hybrid system showed better uniformity**,** reduced mold growth, and preserved aroma and flavor compounds compared to traditional methods. The moisture content consistently reached 6%–7%, making it suitable for safe storage.

Cost Efficiency: The initial construction cost is higher than that of traditional drying platforms but offers long-term economic benefits due to reduced losses and higher bean quality. A cost–benefit analysis indicated a return on investment within 2–3 harvest cycles for medium-scale farmers.

Operational Feasibility: The dryer was easy to operate with, minimal training required. The semi-automated temperature control and ventilation features of the system ensured consistent drying even with user inexperience.

Overall Performance Rating: The Cocoa Seeds Hot Air and Sunshine Dryer is a highly effective and innovative approach to postharvest processing. With further refinement and localization, it holds strong potential for large-scale adoption in cocoa-producing regions, improving livelihoods and product quality.

3. RESULTS AND DISCUSSION

3.1 Results

Table 2: Drying rate of dried cocoa seeds

Initial mass = 25.0 kg

Initial Moisture Content = 55% (db)

	REPLICATE 1			REPLICATE 2			REPLICATE 3			AVERAGE		
Drying Time (hr)	Mass (kg)	Temp. ^{0}C	Moisture Content (%)	Mass (kg)	Temp. ^{0}C	Moisture Content (%)	Mass (kg)	Temp. ^{0}C	Moisture Content (%)	Mass (kg)	Temp. ^{0}C	Moisture Content (%)
1	20	60.0	55.0	19.6	60.0	53.0	10.0	50.0	30.0	16.53	56.67	46.0
2	17.8	58.3	47.2	17.0	58.0	45.0	9.17	51.7	26.25	14.66	56.0	39.48
3	15.6	56.6	39.4	15.0	56.0	40.0	8.33	53.3	22.5	12.98	55.3	33.97
4	13.4	54.9	31.6	13.0	55.0	31.1	7.50	55.0	18.75	11.3	54.97	27.15
5	11.2	53.2	23.8	11.0	53.0	23.5	6.67	56.7	15.0	9.62	54.3	20.77
6	9.0	51.5	16.0	8.5	52.0	17.4	5.83	58.3	11.25	7.78	53.93	14.88
7	7.0	50.0	7.7	6.5	49.0	15.6	5.00	60.0	7.5	6.17	53.0	10.27

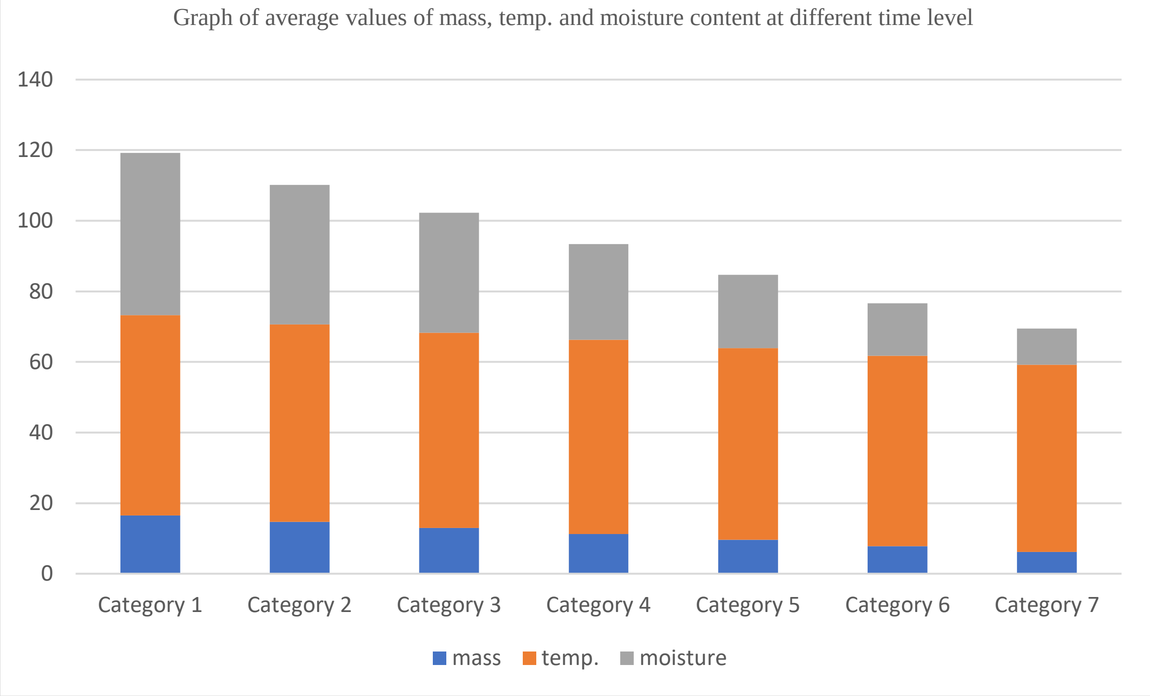


Figure 3: Stacked column chart of mass, temperature, and moisture content over time.

Plate 1: Cocoa seed dryer

3.2 Discussion

Both replications show a steady decrease in mass from 20 kg to ~7kg. This indicates water loss due to drying. Moisture decreases rapidly in the early stages (1–4 h), then slows as it approaches the minimum (7.7%). This is a typical drying curve, with: Constant rate period at the beginning (easy water removal), a falling rate period later (bound water, slower to remove), and a temperature decline from 60°C to 50°C, likely due to energy adjustments or environmental changes. Lower temperatures may slightly reduce the drying rate in later stages.

The second replication closely mirrors the first with slight variation (±0.1g, ±0.2% MC).This indicates good repeatability, the process is reliable and can be used to predict drying behavior. The drying process is effective, and moisture drops from 55% to ~7.7% over 7 h. The mass loss supports moisture reduction. Repetition confirms the reliability. The temperature decline might influence the drying speed at later stages. The data reflect a classic drying behavior with initial rapid loss and later slow reduction due to bound water.

4. CONCLUSION

The drying experiment demonstrates a clear and consistent pattern of moisture and mass loss over time, indicating that drying effectively removes water. Both replications show a steady mass decrease from 20 kg to ~7 kg, accompanied by a rapid decline in moisture content during the initial hours, followed by a slower drying phase. This behavior aligns with the classical drying curve, which consists of a constant rate period and a falling rate period, reflecting the transition from free to bound water evaporation.

The observed temperature drop from 60°C to 50°C may slightly influence the drying rate in later stages but does not significantly disrupt the overall drying trend. The high consistency between replications (±0.1g in mass, ±0.2% MC) highlights the process's repeatability and reliability, making it suitable for predictive modeling and future scaling.

Graphical analysis—such as plotting moisture content, mass, and drying rate versus time—can provide further insights into the drying kinetics, confirming the expected exponential or logarithmic drying behavior. Overall, the drying process is efficient, reproducible, and well-aligned with theoretical drying principles.

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