DEVELOPMENT AND PERFORMANCE EVALUATION OF COCOA-BEANS ACTIVE SOLAR CABINET DRYER PRIMED WITH SOLAR CELLS

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ABSTRACT

Farmers in the rural areas commonly preserve biomaterials by open sun drying. However, this method is associated with problems mostly long drying period, low quality dried products, large drying area. Active direct mode solar cabinet dryer primed with solar cells was developed and tested with cocoa-beans. The cocoa bean samples were dried both in the solar dryer and in open sun drying at layer thickness of 40 mm. Purposive sampling technics and simple descriptive statistics were adopted in identifying the drying layer thickness farmers' normally dry cocoa beans. Heat generation from the dryer was limited to solar energy availability. Solar radiation, ambient relative humidity, wind speed and temperature were common environmental conditions, the drying samples were exposed to. The solar dryer raised the drying temperature from average ambient air temperature of 31.8 °C to average drying air temperature of 43.5°C. Result showed that 200 % drying time was saved when compared with open sun drying method. The analysis also, revealed that the drying efficiency of the solar active dryer was 55% while that of open sun drying was 18%. The drying rate of cocoa-beans samples dried in the solar dryer and open sun drying was $1.4x10^{-4}$ kg/s and 4.5×10^{-5} kg/s respectively. In conclusion, samples dried with solar dryer showed a remarkable appearance, whereas, samples dried in open sun did not have appealing feature as it grew molds.

KEYWORDS: Cabinet dryer, cocoa-beans, thickness, solar energy, sun drying, efficiency

1. INTRODUCTION

Cocoa (*Theobroma cacao L.*) originated from Amazonian region of Brazil and is grown in tropical countries such as Nigeria and others (Dan, 2020). Cocoa beans is mainly consumed as chocolates and widely used in beverages, cosmetics, pharmaceuticals and toiletry products. It is also associated with health benefits such as anticarcinogenic, anti-atherogenic, anti-ulcer, anti-thrombotic anti-inflammatory, immune modulating, anti-microbial, vasodilatory, and analgesic (Dan, 2020). According to Aqua (2022) and Ho and Chen (2008) the density of cocoa beans is 593 kg/m^3. Nwakuba *et al.* (2017) reported that cocoa beans thinly spread in single layer was 1.05 cm thick. Poor infrastructure for processing, storage and marketing in many countries of West African region results to a high proportion of waste, which averaged between 10 and 40 % (Hii *et al*., 2009). Fresh cocoa beans are usually fermented using the heap, tray or box methods for 5 to 7 days depending on the condition of the beans, it is the fermented cocoa beans that is dried, (Vijayana *et al.*, 2016). Currently, sun drying is mostly used in Nigeria by cocoa farmers due to its simplicity, low cost and requires only direct sunlight which is abundant (Vijayana *et al*., 2016). Drying is usually terminated when the dried beans' moisture content is as low as 7.0% (wet basis). However, the traditional open sun drying is associated with a lot of problems. Dina *et al*. (2015) in Samuel *et al.* (2020) opined that the challenge with open sun drying is that at night the ambient temperature decreases and the relative humidity increases; so that the cocoa beans in most cases reabsorbed moisture from the environment, leading to a longer drying time and low-quality dried product. Guda and Gadhe, (2017) reported that cocoa beans dried with solar cabinet dryer raised the dried cocoa beans to higher pH level of 6.3 which is more than normal, given in the range of 5.0 to 5.5.

Energy for human consumption is still very scarce in Nigeria, particularly in the rural areas where there is no electricity and cooking gas. This has adverse effect on processing and preservation of biomaterials. Oghogho *et al.* (2014) and Erin (2016) stated that the total solar energy normally intercepted on the earth surface in a year is 5.5 exa Joules (EJ / yr), and that the solar constant of 1369 W / m^2 floods the atmosphere. They went further to state that Solar energy is the most abundant energy resource on earth and that 173,000 terawatts of solar energy is intercepted on Earth continuously. That is more than 10,000 times the world's total energy use. Eke (2003) opined that about 465W/ m^2 of the solar radiation floods Nigeria as monthly average daily horizontal solar radiation intensity. These works indicated that solar energy which is renewable and ready available to the reach of the local farmers.

A solar collector inclined at a pre-determined angle and mounted facing south, enhances the collection of maximum solar energy radiation (Alamu *et al*., 2010). However, mechanized dryers are cost intensive and out of the reach of local farmers. Therefore, farmers have no option than to continue with the practice of open sun drying. This scenario leaves farmers with incomplete dried biomaterials which is a threat to human health, propagation of post-harvest losses and render production of cocoa-beans uneconomical. This research considered the layer thickness of the drying cocoa-beans. Therefore, the aim of this work was to develop and evaluate active direct mode solar cabinet cocoa-beans dryer, putting into consideration the drying layer thickness of cocoa beans and to compared the drying performance of the solar dryer and that of open sun drying.

2. MATERIALS AND METHODS

2.1. Design Considerations

In order to develop an efficient active solar dryer, the following factors were put into consideration:

1. The geographical location of the experimental site. This is needed for mounting the solar dryer correctly for collection of optimum solar radiation.
2. The size of the dryer.
3. 150 W mono-crystal solar panel for constant power supply.
4. Thermal properties of drying material.
5. Thermal properties of insulating material.
6 Thermal properties of flat-plate solar collector.

2.2. Design Assumptions

The following assumptions were made**:**

1. Collector and drying width of the dryer are equal for free flow of air.
2. The temperature of the drying air in the drying chamber is uniform.
3. The collector air inlet space and the drying chamber air outlet space are equal in size.
4. The ambient temperature is equal to the collector air inlet temperature.

2.3. Design Procedure

The basic standard procedure for evaluating solar dryer performance as recommended by (Leon *et al*., 2002) was followed. The drying system was evaluated using the drying rate, useful heat energy gain, and drying efficiency of the dryer.

2.4. Design Calculations

The following parameters were calculated for the design of the dryer.

2.4.1 Total Heat Energy Required to Dry a given Cocoa-beans.

The total energy required to dry a given quantity of cocoa-beans from initial moisture content to the desired moisture content is as indicated in Equation (1), (Komolafe *et al*., 2014; Koua and Gbaha, 2019).

$$Q = M_d \times C_c \times (T_c - T_a) + M \times C_w \times (T_{c-}T_a) + M_w \times Lv \quad (1)$$

where: Q=Total energy required for drying a given quantity of cocoa-beans kJ, M_d = Mass of bone-dry cocoa-beans kg, C_c = Specific heat capacity of cocoa-beans kJ/kg ^oC, Tc = Collector air outlet temperature ^oC, Ta = Ambient air temperature, M = Mass of initial water content kg, C_w = Specific heat of water kJ\kg$^oC$, W_w = Mass of water to be removed kg, *Lv* = Latent heat of vaporization of water kJ\kg

2.4.2 Collector Useful Heat Energy Gain

The collector useful heat energy gain required to dry a given quantity of agricultural product, was obtained by using the procedure detailed in Equation (2) (Eke, 2003).

$$Q_u = [C_p W_p (T_c - T_a) + L_v W_w)] \qquad (2)$$

where; Q_u = Collector Useful heat energy gain for drying a given quantity of Cocoa-beans (J), C_p = Specific heat capacity of the cocoa-beans (J/ kg °C); W_p = Initial weight of cocoa-beans before drying (kg); T_c = Solar collector air outlet temperature (°C); Ta = Ambient air temperature (°C); L_v = Latent heat of vaporization of moisture from the cocoa-beans (J/ kg).

Latent heat of vaporization of moisture for forced convection solar dryer is presented in Equation (3) (Youcef-Ali *et al.*, 2001; Hii *et al*., 2009; Duffie and Beckman, 2013).

$$L_v = 4186.8(597 - 0.56(T_c + 273.15)) \qquad (3)$$

where; L_v is the Latent heat of vaporization of moisture, T_c= Solar collector air outlet temperature (°C)

2.4.3 Calculation of Quantity of Moisture Removed from the Cocoa-Beans

The amount of moisture removed from the Cocoa-beans was obtained as in Equation (4) (ASABE, 2010; Sallam *et al* 2015).

$$W_w = \frac{W_p\,(M_i - M_f)}{(100 - M_f)} \qquad (4)$$

where: W_w = The amount of moisture removed from cocoa-beans (kg),
M_i = Initial moisture content of the product (% w.b.),
M_f = Final moisture content of the product (% w.b.),
W_w= Initial total weight of product (g)

2.4.4 Calculation of Solar Collector Area

(Holdman, 2002 and Duffie and Beckman, 2013) gave a model equation for calculation of solar collector area, Equation (5).

$$A_c = \frac{Q_u}{F^I t[\tau_t \alpha_p I - U_L(T_c - T_a)]} \qquad (5)$$

where; A_c = Solar collector area, m^2; Q_u = Collector useful heat energy gain required to dry a given quantity of cocoa-beans.(J); t = Drying time (sec.); F^1 = Collector efficiency factor (dimensionless); $\tau_t\alpha_p$ = Transmissibility/absorptivity of glass (0.853). I = Total solar radiation incident on the dryer (W / m^2); T_c = Collector air outlet temperature (°C); T_a = Ambient temperature (°C); $U_{L=}$ Overall heat transfer coefficient. W/m^2 °C.

2.4.5 Determination of Overall Convective Heat Transfer Coefficient

Overall heat transfer coefficient is given in Equation (6) by (Mohanraji and Chandrasekar, 2009 and Duffie and Beckman, 2013).

$$U_L = U_b + U_t \qquad (6)$$

where; U_L = Overall convective heat transfer coefficient W\m^{2}K, U_b = Convective heat transfer coefficient due to base heat loss (W\m^{2}K). U_t = Convective heat transfer coefficient due to top heat loss (W\m^{2}K). Convective heat transfer coefficient due to base heat loss is indicated in Equation (7).

$$U_b = \frac{k}{\Delta_x} \qquad (7)$$

where: Ub = Convective heat transfer coefficient due to base heat loss (W\m^{2}K).
k = Thermal conductivity of sawdust is said to be 0.204 W/m (Yang, 2017),
Δ_x = Thickness of sawdust serving as the insulator.

2.4.6 Calculation of the Convective Heat Transfer Coefficient Due to Top Heat Loss.

Convective heat transfer coefficient due to top heat loss is given in Equations (8 -14) by (Duffie and Beckman, 2013).

$$U_t = \left[\frac{1}{h_{cd}+h_{rd}} + \frac{1}{h_{c\infty}+h_{r\infty}}\right]^{-1} \qquad (8)$$

where: U_t = Convective heat transfer coefficient due to top heat loss (W\m^{2}K).
h_{cd} = Convective heat transfer coefficient between the plate and the top cover,
h_{rd} = The radiation coefficient from the plate to the glass top cover.
$h_{c\infty}$ = Wind or air Convective heat coefficient from the plate to the glass,
$h_{r\infty}$ = Radiation heat coefficient from the glass cover to the sky.

$$U_t = \left[\frac{1}{\frac{1.14(T_p-T_g)^{1-0.0018\left(\frac{T_p+T_g}{2}\right)}}{L^{0.070}} + \frac{\delta\left(T_p^2+T_g^2\right)(T_p+T_g)}{\left(\frac{1}{\varepsilon_p}\right)+\left(\frac{1}{\varepsilon_g}\right)-1}} + \frac{1}{5.7+3.8V+\varepsilon_g\delta\left(T_g^2-T_a^2\right)(T_g+T_a)}\right]^{-1} \qquad (9)$$

where: T_p = Absorber plate temperature (K), L = Height of collector air plenum (m), σ = Stefan-Boltzmann constant (5.67x10^{-8} W/m^{2}K^4), Tg = Glass top cover temperature (K), V = Wind or air speed (m/s). ε_g = Emissivity of glass (0.95), ε_p = Emissivity of absorber plate (0.15). Ta = Ambient air temperature (K)

2.4.7 Calculation of Collector Efficiency Factor

$$Q_{u=A_c}\left\{\tau_g\alpha_p I_T - U_L\left(T_p - T_a\right)\right\} \qquad (10)$$

$$Q_{u=A_c}F^1\left\{\tau_g\alpha_p I_T - U_L(T_c - T_a)\right\} \qquad (11)$$

F^1 = Collector efficiency factor. The other symbols remain as earlier defined, (Duffie and Beckman, 2013).

Equate Equations (10) and (11), make F^1 the subject of the formula

$$Q_{u=A_c}\{\tau_g\alpha_p I_T - U_L(T_p - T_a)\} = F^1 A_c\{\tau_g\alpha_p I_T - U_L(T_p - T_a)\} \quad (12)$$

$$F^1 = \frac{A_c[\tau_g\alpha_p I_T - U_L(T_p - T_a)]}{A_C[\tau_g\alpha_p I_T - U_L(T_c - T_a)]} \quad (13)$$

$$F^1 = \frac{[\tau_g\alpha_p I_T - U_L(T_p - T_a)]}{[\tau_g\alpha_p I_T - U_L(T_c - T_a)]} \quad (14)$$

2.4.8. Drying Efficiency of the Active Solar Dryer.

The drying efficiency of the dryer was obtained using Equation (15) (Ho and Chen, 2008).

$$\gamma_d = \frac{W_w L_v}{AI + E_f} \quad (15)$$

But

$$E_f = \left[\frac{9.81 t V_1 A_f}{1000 E_E E_m}\right]\left[S_p + 0.051\frac{PnV_1^2}{RT_2}\right] \quad (16)$$

where; γ_d = Dryer efficiency for forced convection solar dryer (%). Ww = Mass of moisture be removed (kg) Lv = Latent heat of vaporization kJ/kg, A = Solar collector area, m^2; E_f = Power developed by pump (kJ/s) or fan energy developed with time (kJ), t = drying time (s), V_I = Air velocity in the fan outlet, (m/s), A_f = fan area, (m^2), E_E = Electromotor electric efficiency (%), E_m = Impeller mechanical efficiency (%), Sp = Static pressure, (mm/WC), P = Ambient pressure (Pa), n = Air molecular weight (kg/kmol,) R = Universal gas constant, 8134.4 (kJ/(kmol.K). T2 = Air temperature at the collector exit (K)

2.4.9 Determination of Drying Rate

The drying rate of the product was computed from Equation (17); (Sallam *et al*.,2015).

$$M_{dr} = \frac{M_w}{t_d} \quad (17)$$

where: M_{dr} = Drying rate (kg/hr), M_w = Mass of moisture to be removed (kg)
t_d =Time taken to dry the product (hr)

2.5 Design Description of the Solar Dryer

The design calculations were followed in fabrication of a direct mode active cabinet type solar dryer. The dryer is consisted of the following major features and was properly insulated that there was no heat loss during drying.

2.5.1 The Solar Collector Section

This section is a rectangular box like structure, framed with aluminum square pipe and insulated with saw dust by the sides and base. The saw dust was sand witched with aluminum metal sheet. The inside was painted black to increase heat energy generation in the system. The top cover material was made of transparent glass which permits solar radiation to transmit and fall the black flat-plate body, thereby generating thermal energy in the solar collector section. The collector section equally contained air plenum, inlet and outlet air vents for free flow of air.

2.5.2 Drying Chamber

The drying chamber section was framed with aluminum square pipes and housed with transparent glass. Three sets of crop trays made of stainless net were fixed in the drying chamber. Also, a door which allowed for easy loading and off-loading of the cocoa-beans was fixed in this section.

2.5.3 Blower

A blower which has the feature of sucking out air from the dryer and blowing out the air to the environment, was fixed at exit vent of the drying chamber. The power source was from a recycle deep battery which was charged by a monocrystal solar panel of capacity 150 W. The power source of the blower being from sun made the blower operate continuously during the day, hence, enhanced high drying rate.

The cabinet solar dryer is shown in Figures 1 and 2.
The cabinet solar dryer is shown in Figure 1

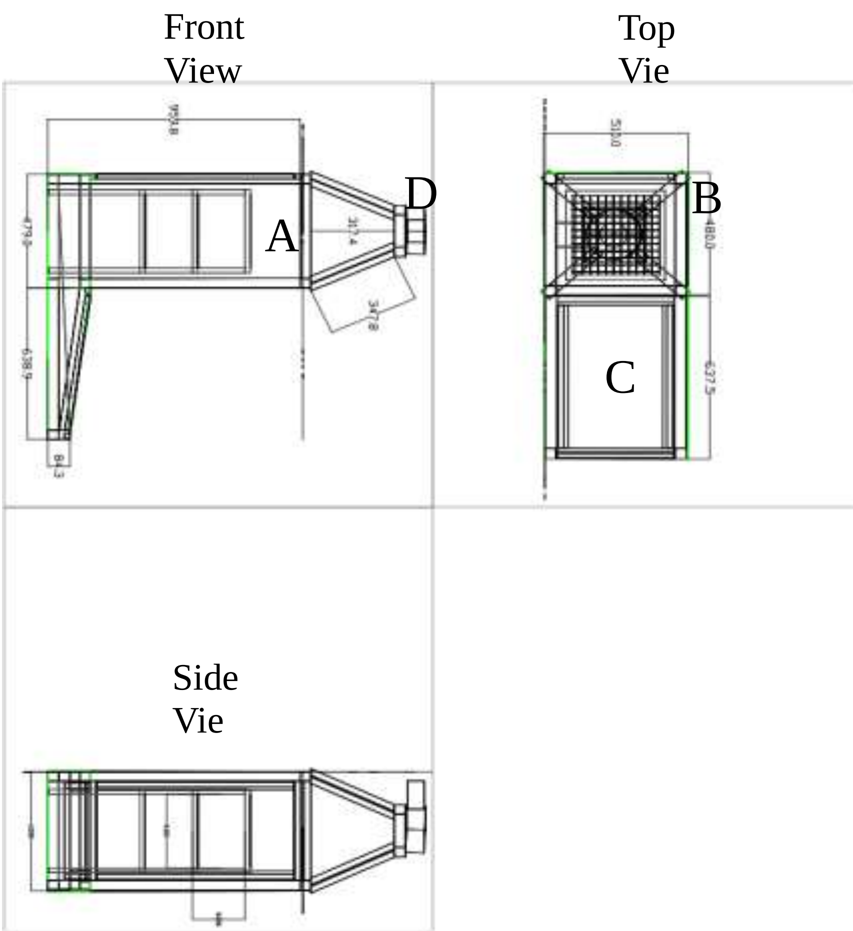

Figure 1: Design drawing of forced convection cabinet solar dryer, showing the three views.

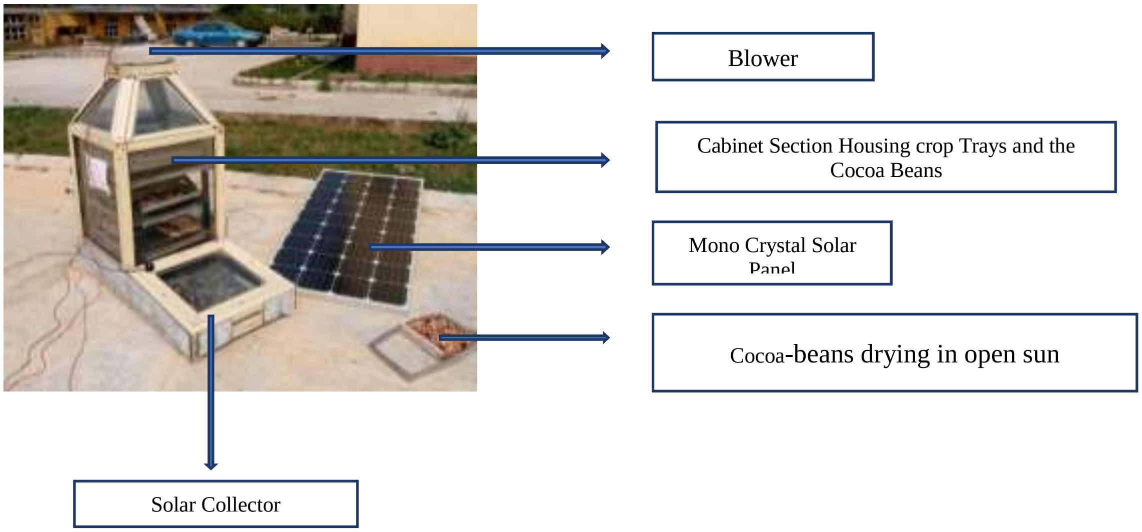

Figure 2: Cabinet solar dryer loaded with cocoa-beans

2.6 Experimental Procedure

2.6.1 Location of experiment

Evaluation of the performance of small-scale force convection cocoa-beans solar dryer took place in the Department of Agricultural and Bioresources Engineering, College of Engineering and Engineering Technology, Michael Okpara University of Agriculture, Umudike. This place is located at latitude5^{o}29' N Longitude 7^o 23' E and Altitude 120 m above the sea level (Akankpo and Igboekwe, 2021).

Eke (2022) reported that the angle of tilt (β) of a solar collector located between Latitude 0^o and 10^o N should be determined as given in Equation (18).

$$\beta = 2.66^o + \ Lat\ \o \qquad (18)$$

where; β is the angle of tilt and Lat ø is the latitude of the collector location.

The collector was mounted at inclination of the determined angle facing south.

2.6.2 Determination of cocoa beans drying layer thickness

Purposive sampling technics was adopted in selecting Umuahia north and Ikwuanno Local government areas as cocoa beans growing communities in Abia State. Four communities were chosen in each of the Local Government Areas. While ten cocoa farmers in each of the eight communities were purposively selected. The farmers were interviewed to identify the drying layer thickness of cocoa beans, when drying in open sun. Drying layer thickness options were; single layer drying, double layer drying, triple layer drying and above triple layer drying. Simple descriptive statistics was adopted in identifying the layer thickness farmers normally dry cocoa beans.

2.6.3 Instrumentation

Highly sensitive equipment (digital Haeni solar radiometer, Engineering prismatic compass, Dole 400 moisture meter, oven, type-T thermocouple omega digital thermometer, digital omega hygrometer, and digital wind-vane anemometer) were used for data collection for solar dryer performance evaluation.

3. RESULTS AND DISCUSSION

3.1 Temperature Distribution

The temperature distribution inside the solar cabinet dryer and the ambient air temperature during the drying operation was shown in Figures 3 and 4. The average drying air temperature of ambient and active solar cabinet direct mode dryer were 31.8 and 43.5 ^oC respectively. The drying air temperature reached its pick between 12.00 noon and 3.00 pm daily. The reason for the higher temperature in the solar dryer was because the solar radiation that passed through the transparent glass housing and fell on the drying cocoa been inside the dryer. This generated heat which was added to that which was generated from the solar collector section, thereby, raising the drying air temperature to 36.8% higher than the ambient air temperature. The blower which generated average air speed of 15 m/s within the solar dryer, did not allow heat to accumulate within the dryer, that may be the reason why the dryer could raise the temperature to only 36.8 % dryer air temperature higher than the ambient air temperature. It was observed that the average value of relative humidity during the period of drying was 25 %. This is because the drying took place in dry season, within December and January. The dryer raising the temperature above the ambient temperature was similar to reports by (Elkhadraoui *et al*., 2015 and Puello, *et al*., 2017).

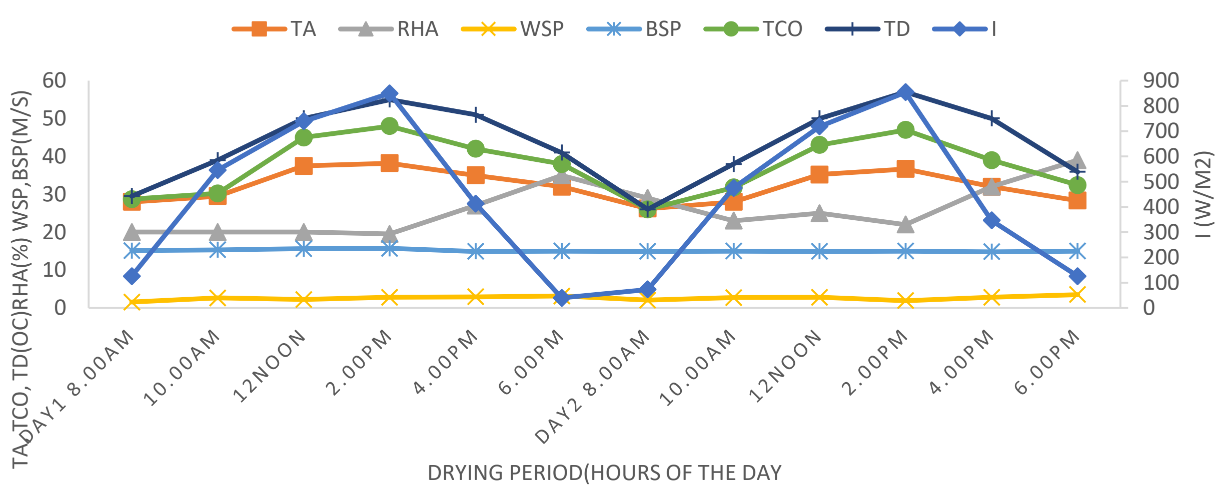

Figure 3: Thermal performance and environmental effect on the Cocoa-beans solar cabinet dryer. (TA, RHA, WSP, BSP, TCO, TD, I are Ambient temperature (^oC), Relative humidity (%), Wind speed (m/s), Blower speed (m/s), Solar collector air outlet temperature (^oC), Drying chamber air outlet temperature (^oC) and Solar radiation (W/m^2) respectively)

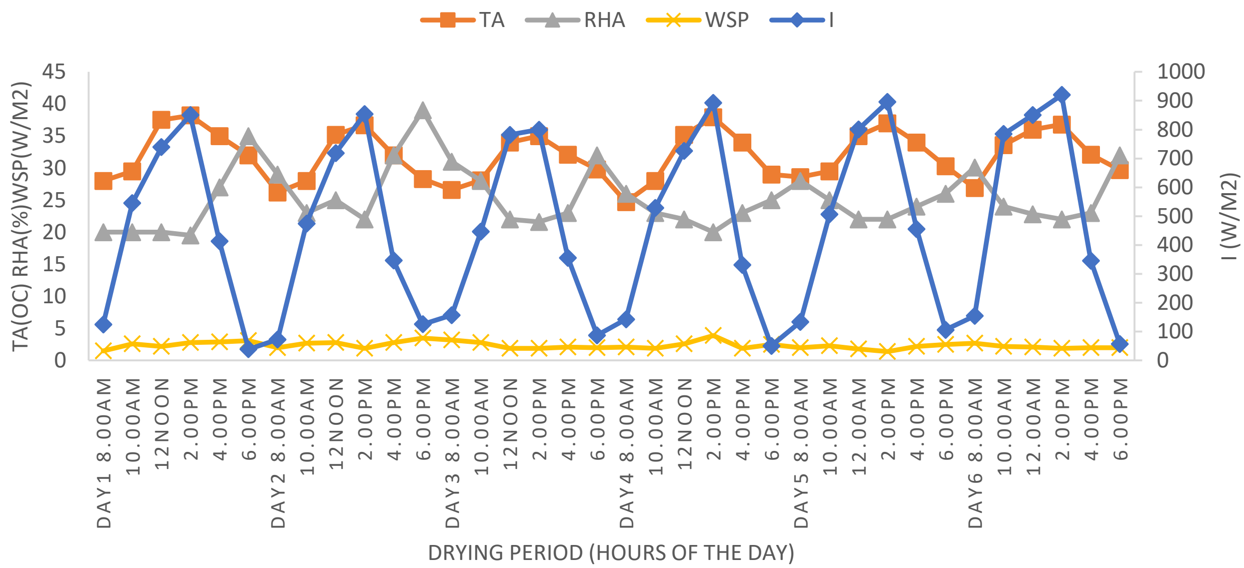

Figure 4: Thermal performance and environmental effect on the Open sun drying. (TA, RHA, WSP and I are Ambient temperature (^oC), Relative humidity (%), Wind speed (m/s) and Solar radiation (W/m^2) respectively).

3.2 Drying Layer Thickness

Out of a total of 80 farmers consulted, 68.75 %, 22.5 % 8.75 % and 0 % admitted that they dry cocoa beans in single layer, double layer, triple layer and above triple layer respectively. Direct measurement showed that single layer thickness was 9.9 mm, double layer thickness was 20 mm, and the triple layer thickness, 30.1 mm. The single layer thickness of 9.9 mm agreed with the work reported by Nwakuba *et al.* (2017), although the percentage of cocoa farmers that dry at single layer was highest, the Researchers decided to double the drying layer thickness to 40 mm, because it will safe drying space and increase the quantity of the product dried per batch. The cocoa beans were dried at initial layer thickness of 40 mm, for both the solar dryer and the open sun drying. This drying thickness was double the higher side the drying layer thickness local farmers normally dry in a batch, as identified in this work.

3.3 Drying Time

The cocoa beans was dried with both solar cabinet dryer and open sun drying method from initial moisture content of 55 to 7 % wet basis. The drying performance of the solar dryer and the open sun drying are presented in Figure 5 and Table 1. Sample in the open sun lasted for 6 days of 60 hours effective drying time. It was observed that the product after drying 3 days in the open sun, the cocoa beans started molding, in the 4th day all the cocoa beans in the open sun molded. However, the product was still drying until the 6th day, when the cocoa beans dried to safe storage moisture content (7 % wet basis). On the other hand, the solar cabinet dryer dried the coco beans within 2 days of 20 hours effective drying period. The cocoa beans dried with the solar dryer was of acceptable appearance. This might be due to the fact that cocoa beans dried inside the solar dryer were protected from environmental contamination, received energy from direct radiation, which raised the heat energy inside the dryer as well as the solar panel supplying constant power for priming the blower.

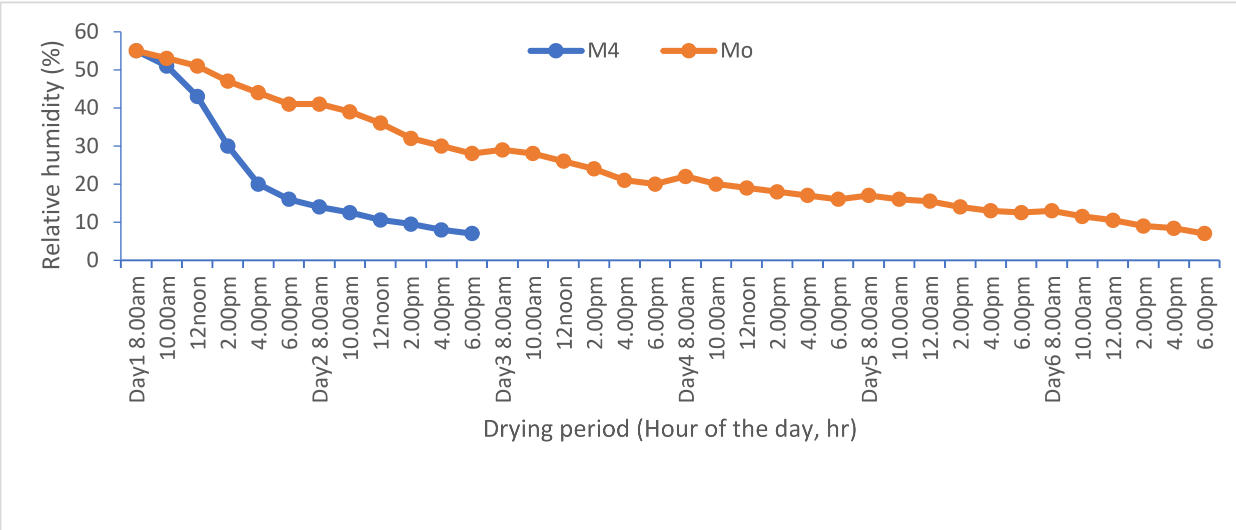

Figure 5: Drying curves, comparison of the moisture contents of cocoa beans dried at 40 mm layer thickness and the open sun drying at the same drying layer thickness. (M4 = curve of moisture (%) removal from sample dried in solar dryer; Mo= curve of moisture (%) removal from sample dried in open sun).

Table 1: Values showing the performance of solar dryer and open sun drying of cocoa beans at drying layer thickness of 40 mm.

Drying method	Drying layer thickness of the product (mm)	Average Ambient tempt. (ºC)	Average Solar radiation (W/m2)	Average Collector air outlet tempt. (ºC)	Average Drying chamber air outlet tempt. (ºC)	Average ambient relative humidity (%)	Average Wind/ Blower speed (m/s)	Drying time (hr)		Moisture content wet basis (%)	
								Total drying time	Effective drying time	Initial	Final
Solar drying	40	31.8	442.0	37.6	43.5	25.3	15	34	20	55	7
Open sun drying	40	32	461.6	-	-	25.3	2.4	130	60	55	7

The solar dryer saved up to 200 % in drying time when compared with open sun drying. The dryer dried the cocoa beans within 20 hours at 10 hours effective drying time per day. The dryer efficiency was calculated as 55 %, while the open sun drying efficiency was 18 %. Cocoa beans dried with the solar dryer achieved 1.4 x 10^{-4} kg/s drying rate and that of open sun recorded 4.5 x 10^{-5} kg/s drying rate. This is due to the fact that the solar dryer. As a result the rate of moisture removal from the drying product was high and unconducive environment for the growth of molds and other microorganisms was created. The cocoa beans drying behaviour agreed with the work done by Iwe *et al*. (2018), on solar dryer for drying Ighu, and the report by Morad *et al.* (2015) for drying peppermint.

4. CONCLUSION

In this study, active direct mode solar cabinet cocoa beans dryer, primed with solar cells was developed and tested. The Cocoa beans drying layer thickness normally dried by local farmers was determined. The solar dryer developed dried twice the quantity of product normally dried in open sun at a given drying space. The drying curves showed that the solar dryer resulted in considerable reductions in drying time as compared to open sun drying. The increase in temperature inside the dryer and forced convection air flow rate, permitted the faster moisture removal rate, higher drying efficiency and high-quality dried cocoa beans.

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