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Thermal Efficiency of Indirect Solar Dryer Using Pebbles as Absorber during Cocoa Drying

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Abstract

The effect of a storage system on drying time and estimation of drying parameters of cocoa beans using an indirect solar dryer with a sensible heat energy storage system (stones which act as both absorber and heat storage media) is the main subject of this article. This dryer, which uses stones as storage material and is made of wood and plywood, was used to dry a quantity of 5 kg of fermented cocoa beans. The drying parameters for the drying curves and the drying efficiency of cocoa beans were established and studied. The drying curves were modelled from semi-empirical models. The results showed that the moisture of cocoa beans decreased from 60% to 7% in wet basis. With a solar collector and drying efficiency of 40% and 34%, respectively. And this with a maximum average difference temperature between the drying air and the ambient temperature of 13.25˚C day or night. The best concordances are obtained with R^2 values of 0.9983, 0.9843, 0.9813 and 0.9837 respectively from the models of Hii, Jena and Das, Demir *et al.* and Alibas.

Keywords

Cocoa Beans, Indirect Solar Dryer, Heat Storage, Drying Curve, Solar Energy

1. Introduction

The cultivation of cocoa beans (Theobroma cacao) is one of the main export crops of Côte d'Ivoire. Indeed, with a production of 2.2 million tonnes in 2022, Côte d'Ivoire is the world's leading producer. Cocoa marketing accounts for 20% of gross domestic product and 40% of export earnings [1]. Small producers do the drying of cocoa beans almost entirely in the traditional way. Indeed, more than 60% of the dried cocoa in Africa is traditionally made by exposing the beans directly to the sun [2].

This type of sun drying is widely practiced by spreading the beans on wooden, bamboo, plastic or concrete racks during sunshine hours. Beans are regularly turned over manually and a person is required to protect the beans in case of rain. Although freely available, this laborious drying method depends of weather conditions and extends over several days (7 to 22 days), exposing the beans to environmental contamination [3]. This contributes to producing beans with bad qualities, because a long drying period exposes the beans to mold growth [4]. Although inexpensive and freely available to all producers, this method is ineffective during heavy rains periods and high humidity.

Given the importance of cocoa cultivation in the economy of the Ivory Coast, it is necessary to ensure the good quality of the beans harvested and dried. Quality depends largely on the drying process. Fermentation and drying are the main steps in the cocoa bean drying process. These steps play a very important role in the formation of smell and taste. These steps must be carried out properly in order to obtain cocoa beans with good quality [5]. After fermentation, the purpose of drying is to reduce the water content of cocoa beans, until it reaches a value between 5% and 8% in wet basis [6].

A cocoa bean with good quality, usable by the chocolate and pharmaceutical industries must meet among others the following criteria: moisture content (5.5% - 8% wet basis), pH (3.8 - 5.5), fat content (55% - 56%), shell contents (15% - 17%), brown beans, not mouldy, high antioxidant activity, acetic acid, caffeine, Crispy dried beans [7]-[9].

Various drying methods and techniques, as well as their impact on the quality of dried beans, have been the subject of several studies.

In order to obtain good quality beans that can be sold, solar dryers were built and applied to the drying of cocoa beans.

Koua *et al.* [10], in their work on cocoa beans drying in an indirect solar air-forced dryer, studied the coefficients of volume shrinkage, the effective moisture diffusivity and the drying kinetics of cocoa beans. They concluded that the desorption isotherms of cocoa beans have a sigmoid appearance, the drying of cocoa beans takes place during the decrease phase, the effective diffusivity of moisture decreases as the water content decreases and the volume shrinkage decreases linearly with the decrease in water content.

Banboye Frederick Dzelagha *et al.* [2], in an article, reviewed recent studies on different drying methods and quality parameters of cocoa beans. They report that for the open drying method called natural drying, the parameters to optimize to improve the drying speed are the drying equipment and the position of the trays. This is because this drying method is highly dependent on the intermittent nature of the sun. About the drying using solar dryers, the parameters to be optimised are the construction materials, the solar air collector inclination angle and air extractor. And this in order to improve the energy absorbed and drying parameters.

Yeboah [11] and Manoj, together with Manivannan [12], have separately developed a mathematical model to simulate the properties of drying air and moisture content at equilibrium for a solar-greenhouse dryer for cocoa bean drying. The moisture content of cocoa beans was successfully reduced from 50% to 7% for 7 days.

D. O. Oke and K. F. Omotayo [13], dried cocoa beans using a forced convection solar dryer. They studied the effect of this drying method on the quality of the beans. They concluded that this drying method is appropriate drying of cocoa beans during for 2 to 7 day and for drying temperatures ranging from 35˚C to 55˚C.

The artificial drying of cocoa beans is reported in literature. The majority of research has focused on reducing drying time [14] [15].

Juanito D. Burguillos and al [16], built and tested an indirect forced convection solar dryer by drying cocoa beans. The beans moisture content has decreased from 55% to 7.5% in wet basis with a drying temperature range between 40˚C and 70˚C. They report in their work that the dried beans obtained are of good quality.

The temperature range commonly used to dry products is between 40˚C and 60˚C. However, a very high temperature could have a negative effect on product quality [17].

Degradation of agricultural products is also linked to the extension of drying time, when solar irradiation is low or during the night. To reduce drying time and thus improve product quality, it is necessary to integrate a heat storage unit into the drying system in order to continue drying even in no sunlight period [18].

Several experimental and theoretical studies on indirect solar dryers with a sensible heat storage system are reported in the literature.

Chaouch *et al.* [19] studied the performance of a forced convection solar dryer with a sensible heat storage unit located below the absorber and in the drying chamber for drying camel meat. The heat storage system placed inside the heat collector system improved thermal efficiency by 28%. Also the storage unit inside the drying chamber improved thermal efficiency by 11.8%. Heat storage units coupled to the heat collector and drying chamber allowed an additional hour of drying per day.

Vijayan *et al.* [20] have studied an indirect solar dryer with a sensitive heat storage unit under the heat collector (absorber). They reported that the drying time with this dryer was reduced by 3 hours compared to the open air drying in the sun. They also mentioned that the use of the storage unit has reduced the fluctuations inside the collector outlet air temperature and achieved a thermal efficiency of 22% for the heat collector.

Kamble *et al.* [21] experimentally studied an indirect solar dryer with a solar air heater and using gravel as storage material for drying green peppers. The results of their work showed that the use of a storage unit allowed drying to be extended for 4 hours after sunset. This reduced the drying time by 48 hours compared to the sun-drying method. They reported a drying efficiency of 34%.

Nabnean *et al.* [22] have built a solar dryer with a sensible heat storage system (a water cum TES tank) for drying 100 kg of tomatoes. They successfully dried

100 kg of tomatoes in 4 days, reducing their moisture content from 62% to 15% in wet basis. They also found an efficiency of the solar air collector ranging between 21% and 69%.

Amer *et al.* [23] designed a solar air dryer with a heat exchanger combined with a thermal storage system and an auxiliary heat source for drying bananas. The heat unit is used to produce the water vapour required for the drying process. During no sunlight periods, the production of humid air is done by the heat exchanger by removing heat from the hot water unit. They found a thermal drying efficiency of 31.7%.

Reyes *et al.* [24] dried mushrooms with a solar air dryer consisting of a solar air heater, a heat storage unit using paraffin wax as phase change storage material (MCP), an electric heat source and a fan. They found thermal efficiencies ranging from 22% to 67% for the collector and between 10% and 21% for the storage unit. They also report that the use of the storage unit reduces the consumption of electrical energy by 40% to 70%.

Shalaby and Bek [25] studied an indirect forced convection solar dryer with latent heat storage unit also using paraffin wax as a storage material for drying medicinal plants. Their studies showed that the temperature inside the drying chamber is maintained above ambient temperature between 2.5˚C and 7.5˚C after sunset.

However, there is very little research on the use of indirect solar dryers with storage systems for drying cocoa beans. This work includes the work of Dina *et al.* [26] and A.O. Fagunwa, *et al.* [27].

Dina *et al.* [26] experimentally studied the performance of an indirect solar dryer with a heat collector and a desiccant material used as storage material for drying cocoa beans. Two adsorbent materials ($CaCl_2$; calcium dichloride) and Na86 $[[(AlO_2)_{86} (SiO_2)_{106}]_{264} H_2O$ (molecular sieves, 13X)] were placed outside the drying chamber during the day to remove moisture from them. And then the adsorbent materials are introduced into the drying chamber during the night to absorb the moisture contained inside the product to be dried. Thus, in no sunlight periods, the adsorbent lowers the humidity inside the drying chamber. The results of their work showed that the use of a desiccant unit reduced drying time and specific energy consumption.

A.O. Fagunwa *et al.* [27] built a solar dryer with a heat storage system for the continuous drying of cocoa beans. The results of their studies showed that this solar dryer allowed cocoa beans to dry effectively by reducing the cocoa beans moisture content to a healthy level of 3.6% in wet basis within 72 hours. And the amount of heat needed for the drying process during no sunlight periods can be stored properly in gravel placed in a glazed location.

The objective of this work is to study the thermal performance of an indirect forced-convection solar dryer with a storage system, as well as the drying kinetics during the drying of cocoa beans and the effect of the storage system on the drying time.

2. Presentation and Description of the Solar Dryer

Figure 1 and **Figure 2** show a photo and detailed schematic of the indirect solar dryer made of plywood and wood, respectively. It consists of a solar air heater, connected to a drying chamber. The solar air heater is a sensible heat energy storage unit, using black painted stones as absorber and heat storage material. It is 1.88 m long (L), 0.82 m wide (l) and 0.15 m high (h). A glass of thickness $e = 5\ \text{mm}$ and 1.54 m^2 surface (A_g) is placed above the heat storage to reduce thermal losses upwards. The gap of 0.15 m between the glass and the bottom of the storage is filled with stones to store heat and thus maintain a drying temperature above ambient temperature [28].

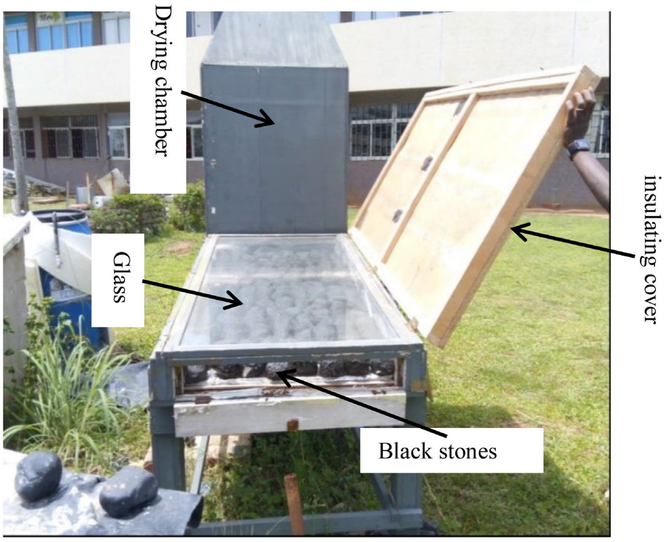

Figure 1. Photo of the solar dryer.

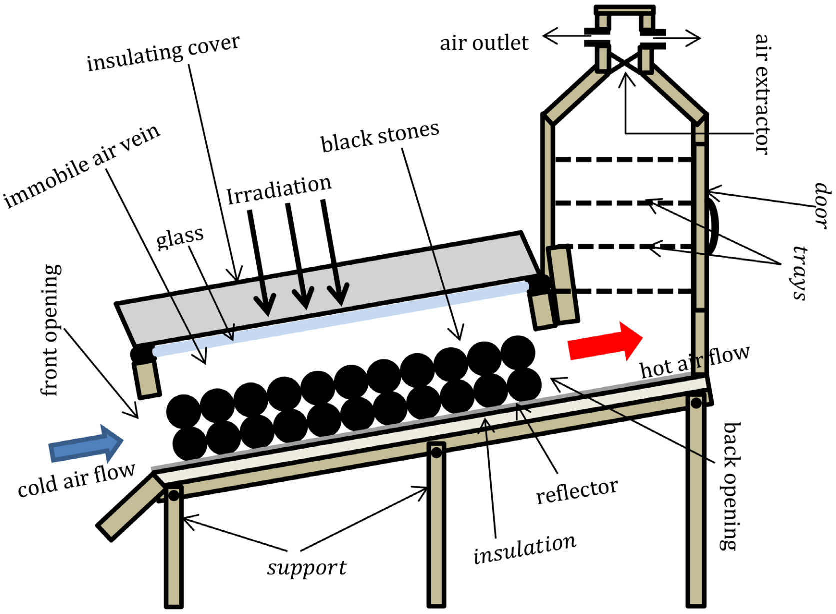

Figure 2. Schematic of the operation of the solar dryer.

The 0.12 m high stone bed is supported by a reflective plate to increase the amount of heat reaching the stones and reduce heat loss downwards. The stones are river pebbles covered with a thin layer of aluminum and painted black (**Figure 3**). The aluminium layer should increase the thermal conductivity of the stones. The thermal and physical properties of the stones are recorded in **Table 1**.

Figure 3. Photo des pierre.

Table 1. Thermal and physical characteristics of stones [30].

Parameter	Nomenclature	Value	Unit
Density	ρ_P	2940	kg·m^{-3}
Heat capacity	C_P	880 ± 50	J·kg^{-1}·K^{-1}
Thermal conductivity	K_P	2.5	W·m^{-1}·K^{-1}
Average diameter of stones	d_P	0.04	M
Mass flow rate	$\dot{m}_f$	0.08	kg·s^{-1}
Porosity of the stones bed	ε	0.47	
Mass of stones	m	145	Kg

The distance between the last stone level and the glass is 0.03 m. The storage is insulated on its side faces with polystyrene of thickness 0.020 m and thermal conductivity 0.047 W·m^{-1}·˚C^{-1}. The bottom of the storage unit is also insulated with 0.020 m thick polystyrene. The solar air collector has an insulating cover, to reduce heat losses upwards, during no sunlight periods. The solar air solar collector is tilted at an angle of 10˚, relative to the horizontal [29]. The storage unit has two rectangular openings 0.12 m high and 0.82 m wide at its entrance and exit.

The storage unit is connected by its outlet to a drying chamber. The drying chamber which is made of 0.020 m thick plywood, 1 m high, 1m wide and 1m long. It is designed to receive four (4) trays on which cocoa beans are spread. The trays are distant to 0.10 m from each other. Each tray is made of wood structure with rubber nets of 1 m^2 surface to facilitate the passage of air. The drying chamber has a door on one side through which the beans can be placed or removed. At the exit of the drying chamber, is placed a fan power of 4.2 W, to force the passage of air through stones.

When the solar collector is exposed to sunlight, the black stones inside the solar air heater are irradiated by the sun's rays that pass through the glass cover. Thus the stones heat up, storing the energy received from the sun. At the same time, air at ambient temperature enters the solar collector through an opening located in front of the solar air heater. The air passes through the hot stones, recovering all or part of the energy stored by the stones.

The heat-transfer fluid, which is now hot, leaves the solar collector through the opening at the back of the solar air heater, enters the drying chamber, passes through the products, spread on the trays. Thus, the heat transfer fluid removes the water contained in the products. Then the air loaded with the cocoa beans moisture, comes out of the drying chamber through a chimney.

3. Measurement Equipment and Drying Procedure

3.1. Preparation of Cocoa Beans

The cocoa beans were harvested in ivory coast in the Yamoussoukro region. After harvest, the cocoa beans were warped and fermented over five days. After fermentation, the beans obtained have a mass of 10 kg with an initial moisture content of 60% in wet basis. Then 5 kg of the beans are placed on a tray in the drying chamber of the solar dryer and 5 kg are spread on a tray and exposed directly to the sun, to be dried (**Figure 4**).

Figure 4. Photo of the cocoa beans in the drying chamber and exposed to ambient air.

3.2. Measurement Materials

The measuring unit consists of:

Figure 5. Probe photo DS18B20.

- ✓ of sixteen (25) temperature probes which are dallas temperature probes ds18b20 (Figure 5);
- ✓ a pyranometer (Figure 6);
- ✓ a 0.01 g precision electronic balance for mass measurement (Figure 7).

Figure 6. KIPP ZONEN Solarimeter.

Figure 7. Electronic balance.

Temperature probes are placed in different locations of the solar air heater to measure temperatures of the stones, of the glass cover and of the air of collector inlet and outlet.

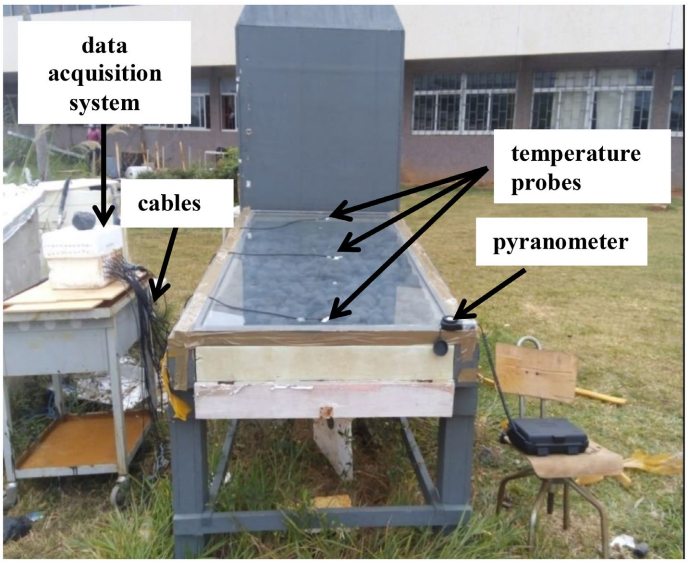

Figure 8. Photo of the solar dryer connected to the data acquisition system.

Once measured, these temperatures are recorded and stored in the data acquisition system. Then, using USB cable communication, these measures are transmitted to a computer for processing. Figure 8 and Figure 9 show a picture and an illustration of the dryer connected to the data acquisition system, respectively.

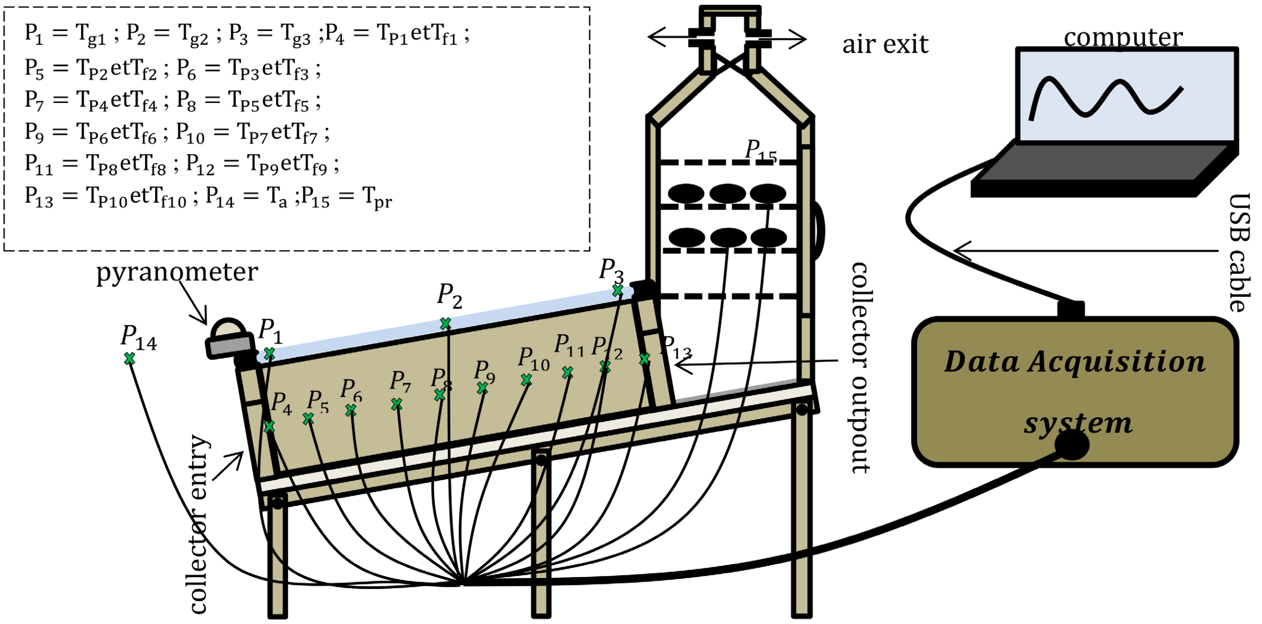

Figure 9. Illustration of the data acquisition system connected to the solar dryer.

In Figure 9, we have:

P : position of the probe; T_g : temperature of the glass; T_P : temperature of the stone; T_f : temperature of the heat transfer fluid (air); T_a : ambient temperature; T_{Pr} : temperature at the product.

The cocoa beans from the drying chamber are placed on the electronic balance for weighing.

4. Performance of the Solar Dryer

Energy and exegetic analysis are seen as an essential tool for the design, analysis and optimization of thermal systems [31].

4.1. Energy Analysis

This analysis will allow us to establish the efficiencies of the storage system and the drying. Figure 10 illustrates the thermal exchanges within the storage unit and the components of the storage unit with the external environment.

$h_{c,g-a}$ and $h_{c,g-p}$, are respectively the convection exchange coefficients between the glass and the ambient environment and between the glass cover and the stones. And $h_{r,g-a}$ et $h_{r,g-p}$, respectively, the radiation exchange coefficients between the glass and the sky and between the glass and the stones.

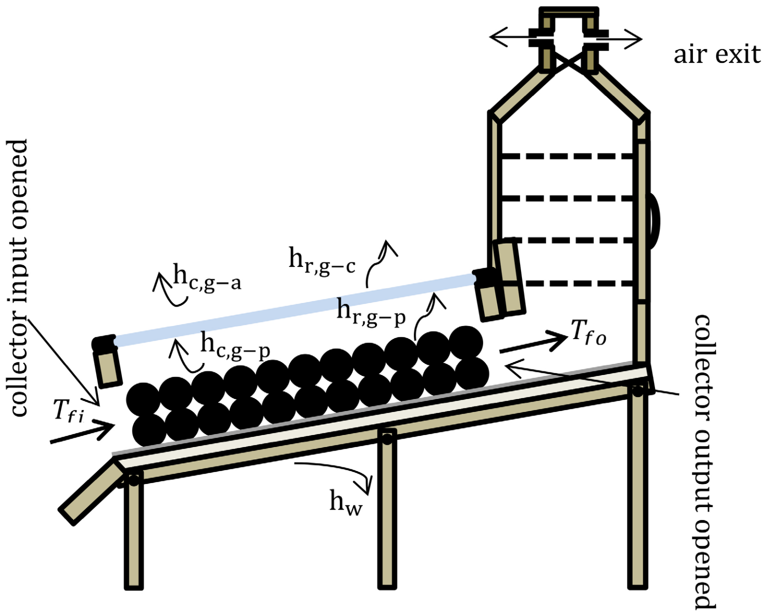

Figure 10. Thermal balance of the collector solaire.

With:

- $h_{r,g\text{-}c} = \sigma \varepsilon_v \times \dfrac{T_g^4 - T_c^4}{T_g - T_a}$ [32]; (1)
- $h_{r,g\text{-}p} = \dfrac{\sigma}{\dfrac{1}{\varepsilon_g} + \dfrac{1}{\varepsilon_p} - 1} \times \dfrac{T_p^4 - T_g^4}{T_p - T_g}$ (2)

where

$$T_C = 0.0552 \cdot T_a^{1.5} \tag{3}$$

$$\sigma = 5.67 \times 10^{-8}\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}\ [32] \tag{4}$$

ε_g and ε_p are respectively the emissivity of the glass and stones.

- $h_{c,g-a} = h_w = 5.7 + 3.8v$; (relation of Mc Adam, 1954) [32] (5)
- $h_{c,g-p} = \dfrac{N_u K_f}{d}$ (6)

Nusselt number N_u is given by Hollands, Unny, and Konicek, 1976 [32]

$$\begin{aligned} N_u = {} & 1 + 1.44 \times \left\{ 1 - \left[1708 \left(\sin 1.8\theta \right)^{1.6} \big/ \left(R_a \cos\theta \right) \right] \right\} \\ & \times \left[1 - \left(1708 / \left(R_a \cos\theta \right) \right) \right] + \left[\left(R_a \cos\theta / 5830 \right)^{1/3} - 1 \right] \end{aligned} \tag{7}$$

The thermal balance of the heat storage unit is given by the following relation (8):

$$P_a = P_u + P_{st} + P_{lost} \tag{8}$$

With P_a, P_u, P_{st} and P_{lost} are respectively the absorbed power, the useful power, stored power and the heat storage unit lost power.

The absorbed, useful, stored and lost powers are given by the relations (9), (10), (11) and (12) [32]

$$P_a = \left(\alpha_p \tau_g\right) A_g I \tag{9}$$

$$P_u = \dot{m} C_a \left(T_{fo} - T_{fi}\right) \tag{10}$$

α_p and τ_g, are respectively the absorptivity of the stones and transitivity of the glass cover and A_g is the glass cover surface.

$$P_{st} = m_p C_p \left(T_{pf} - T_{pi}\right) \times \frac{1}{\Delta t}; \tag{11}$$

$$P_{lost} = U_T A_g \left(T_P - T_a\right) \tag{12}$$

With

$$\dot{m} = \rho v_f S \tag{13}$$

U_T, the total loss coefficient is obtained by adding the forward U_{av} and downward U_{ap} loss coefficients of the storage unit. Lateral losses are neglected. Thus:

$$U_T = U_{av} + U_{ar} \tag{14}$$

The expression of the forward loss coefficient is:

$$U_{av} = \left(\frac{1}{h_{c,g\text{-}a} + h_{r,g\text{-}c}} + \frac{1}{h_{c,g\text{-}p} + h_{r,g\text{-}p}}\right)^{-1} \tag{15}$$

The expression of the downward loss coefficient is:

$$U_{ar} = \left(\frac{1}{h_w} + \frac{1}{k_{is}/e_{is}} + \frac{1}{k_b/e_b}\right)^{-1} \tag{16}$$

It should be noted that as the system of production of hot air, behaves both as a solar air collector and as a heat storage system, then the useful power is less or equal to the stored power. Thus, in the following it will be considered that: $P_{st} = P_u$.

- Storage system efficiency

The efficiency of the storage unit η_c, defined as the ratio between the useful power and the power absorbed by the stones has for expression:

$$\eta_c = \frac{\dot{m} C_a \left(T_{fo} - T_{fi}\right)}{\left(\alpha_p \tau_g\right) I A_g} \tag{17}$$

- Drying efficiency

The drying's one, marked η_d, which is the ratio of the energy required to evaporate the moisture content from the product to the energy supplied to the solar dryer, has the following expression [34]:

$$\eta_d = \frac{m_w L_v}{\left(I A_g + P_f\right)\Delta t} \tag{18}$$

where

$$L_v\left(T\right) = 2.5018 \times 10^3 - 2.378 \times T \quad [35] \tag{19}$$

With m_w, the evaporated mass water ; L_v, the latent heat of vaporization; P_f, the power of the fan.

4.2. Drying Parameters

4.2.1. Moisture Content

The initial moisture content of the product in wet basis X_i, which is the weight of water present in the product per mass unit of wet product and the moisture content at any time time t $X(t)$ are given by the relations (20) [36], (21) and (22) [37] according to:

$$X_i = \frac{m_i - m_s}{m_i} \tag{20}$$

$$X(t) = \frac{m(t) - m_s}{m_i} \tag{21}$$

Either again:

$$X(t) = X_i - 1 + \frac{m(t)}{m_i} \tag{22}$$

where m_i and $m(t)$ are respectively the mass product at initial and at any time *t*.

The reduced moisture content X_R, is determined as follows [38]:

$$X_R = \frac{X(t) - X_e}{X_i - X_e} \tag{23}$$

X_e is the equilibrium moisture content.

Several studies [39]-[41] report that the moisture content at equilibrium X_e, is very low compared to the initial moisture content X_i and the moisture content at each time *t*, $X(t)$. Thus in the previous study, the reduced water content will be reduced to the expression below:

$$X_R = \frac{X(t)}{X_i} \tag{24}$$

4.2.2. Drying Rate

The relation (25) below allows to determine the drying rate V_d:

$$V_d = -\frac{\mathrm{d}X(t)}{\mathrm{d}t} = \frac{X(t) - X(t+\mathrm{d}t)}{\mathrm{d}t} \tag{25}$$

4.2.3. Drying Modelling

In the selection of mathematical models predicting the drying of cocoa beans with our dryer, the correlation coefficient R^2, the reduced statistical parameter χ^2 and the square root of the mean error RMSE are used to determine the quality of the modeling. The criteria for good modelling are a very high value of R^2 and very low values of χ^2 and du RMSE [42].

The values of these three parameters are obtained from the relations 26, 27 et 28 [43] [44].

$$R^2 = 1 - \frac{\sum_{j=1}^{N}\left(XR_{exp,i} - XR_{pre,i}\right)^2}{\sum_{j=1}^{N}\left(\overline{XR}_{exp} - XR_{exp,i}\right)^2} \tag{26}$$

$$\mathrm{RMSE} = \left[\frac{\sum_{i=1}^{N}\left(XR_{exp,i} - XR_{pre,i}\right)^2}{N}\right]^{\frac{1}{2}} \tag{27}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(XR_{exp,i} - XR_{pre,i}\right)^2}{N - n} \tag{28}$$

With:

$XR_{exp,i}$: the *i*-th experimental value of reduced moisture content;

$XR_{pre,i}$: the *i*-th predicted reduced moisture content;

N : the number of observed values;

n : the number of constants in the drying model.

The semi-theoretical models commonly used to describe thin layer drying are given in Table 2.

Table 2. Mathematical models used to model the drying curves.

Model name	Equation of the model	References
Lewis	$XR = \exp(-kt)$	Ayansu (1997) [29]
Henderson and Pabis	$XR = a\exp(-bt)$	Mahmutoglu *et al.* (1996) [30] [31]
Page	$XR = \exp(-kt^n)$	Basunia and Abe (2001) [31] [32]
Modified Page	$XR = \exp\left[-(kt)^n\right]$	Togrui and Pehlivan (2002) [33]
Logarithmic	$XR = a\exp(-kt) + c$	Yaldiz *et al.* (2001) [27]
Two-term model	$XR = a\exp(-k_0 t) + b\exp(-k_1 t)$	Lahsasni *et al.* (2004) [34]
Two-term exponential	$XR = a\exp(-k_0 t) + (1-a)\exp(-k_0 at)$	Midilli and Kucuk (2003) [35]
Verma *et al.*	$XR = a\exp(-kt) + (1-a)\exp(-gt)$	Doymaz (2005) [36]
Approximation of diffusion	$XR = a\exp(-k_0 t) + (1-a)\exp(-k_0 bt)$	Usub *et al.* (2009) [24]
Wang and Singh	$XR = 1 + a\cdot t + b\cdot t^2$	Usub *et al.* (2009) [24]
Midilli	$XR = a\cdot\exp\left(-k\cdot t^n\right) + b\cdot t$	Meisami-asl *et al.* (2009) [37]; Ojediran and Raji (2010) [37]
Weibull	$XR = \exp\left[-(t/a)^n\right]$	Meisami-asl *et al.* (2009) [37]; Ojediran and Raji (2010) [38]
Logit	$XR = a/\left(1 + a\cdot\exp(k\cdot t)\right)$	Meisami-asl *et al.* (2009) [37]; Ojediran and Raji (2010) [38]
Hii	$XR = a\cdot\exp\left(-k\cdot t^n\right) + c\cdot\exp\left(-g\cdot t^n\right)$	Saheeda Mujaffar (2020) [39]
Weibull distribution	$XR = a - b\cdot\exp\left(-k\cdot t^n\right)$	Saheeda Mujaffar (2020) [39]
Jena and Das	$XR = a\cdot\exp\left(-k\cdot t + b\cdot t^{1/2}\right) + c$	Saheeda Mujaffar (2020) [39]
Demir *et al.*	$XR = a\cdot\exp\left(-k\cdot t^n\right) + c$	Saheeda Mujaffar (2020) [39]
Alibas	$XR = a\cdot\exp\left(-k\cdot t^n + b\cdot t\right) + g$	Saheeda Mujaffar (2020) [39]
Logistic	$XR = a_0/\left(1 + a\cdot\exp(k\cdot t)\right)$	Saheeda Mujaffar (2020) [39]

5. Uncertainty Analysis

The uncertainty analysis is about measured and calculated parameters.

1) Uncertainties on the measured parameters

The measured parameters are temperatures. To determine uncertainties and errors in temperature measurements, a digital thermometer is used. Then a series of multiple measurements is made using each of the 24 probes and the digital thermometer under the same experimental conditions to determine statistically representative uncertainties that can be calculated. The relative uncertainty is then determined by taking the differences between the digital thermometer and probe readings. This difference is then related to the numerical difference. A mean of relative uncertainties is finally made according to the formula:

$$\overline{\left(\frac{\Delta T}{T_{dT}}\right)} = \frac{1}{n}\sum_{i=1}^{n}\frac{T_{dT} - T_{PT}}{T_{dT}} \tag{29}$$

This average gives a relative uncertainty of 2% for the temperatures measured by the probes.

2) Uncertainties on the calculated parameters

The error of experimental results based on uncertainties in primary measurements is performed using the Kline and McClintock report [26] as reported by Jia *et al.* [27]

$$\Delta y = \left[\left(\frac{\partial f}{\partial x_1}\right)^2 (\Delta x_1)^2 + \left(\frac{\partial f}{\partial x_2}\right)^2 (\Delta x_2)^2 + \cdots + \left(\frac{\partial f}{\partial x_n}\right)^2 (\Delta x_n)^2\right]^{0.5} \tag{30}$$

where f is the given function of the independent variables, x is one of the variables in the function and Δx is the absolute error associated with the variable. The relative error is represented by the following relation:

$$\frac{\Delta y}{y} = \left[\left(\frac{\partial f}{\partial x_1}\right)^2 \left(\frac{\Delta x_1}{y}\right)^2 + \left(\frac{\partial f}{\partial x_2}\right)^2 \left(\frac{\Delta x_2}{y}\right)^2 + \cdots + \left(\frac{\partial f}{\partial x_n}\right)^2 \left(\frac{\Delta x_n}{y}\right)^2\right]^{0.5} \tag{31}$$

The calculated parameters are the temperatures calculated by the model and the efficiency calculated from the measured parameters. The temperatures calculated by the model are obtained from measured heat flux and ambient temperature, taking into account uncertainties in measurements of these two parameters. The analysis of the results shows an overall accuracy of about 2%. By the same method, the overall accuracy of the solar collector efficiency is determined to 0.4% and 1.1% for drying efficiency according to temperatures.

6. Results and Discussions

The experimental study on the drying process of cocoa beans took place from Wednesday, April 09, 2022 to Saturday, April 12, 2022, at the Department of Energy Engineering of the Félix Houphouët Bobigny Polytechnic Institute in Yamoussoukro, located between latitude 6˚15 and latitude 7˚35 N and longitude 4˚40 and longitude 5˚40 W. The experimental study focused on the energy and drying performance of the solar dryer and on the quality of the beans obtained with this dryer. For this purpose, a comparative study of the drying of cocoa beans in the open air and with the solar dryer was carried out.

Figure 11 shows the evolution of the irradiation, ambient temperature, stones temperature and collector air outlet temperature with time. We observe that during the drying period, the irradiation has an ascending and descending phase with an irregular character. This irregular character is explained by the passage of the clouds some time.

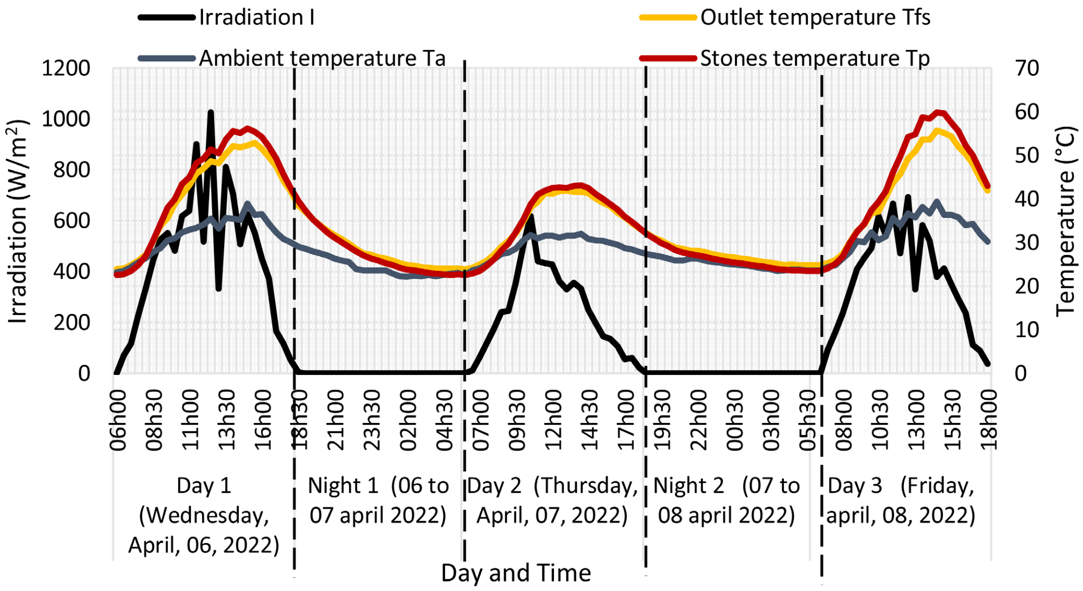

Figure 11. Evolution of solar irradiation, ambient temperature, stones temperature , solar air heater outlet temperature.

The first and third days have an ascending phase starting from 6:00 to 12:30 and a descending phase from 12:30 to 18:30. On the second day, the ascending phase takes place from 06:00 to 10:30 and the descending phase from 10:30 to 18:30.

The maximum and average values of irradiation as well as total energy received for each of the three days are recorded in Table 3 below.

Table 3. Maximum and average irradiation and total energy received.

	Irradiation ($w \cdot m^{-2}$)		
	maximum value	average value	total energy received
Day 1	1026 W/m²	446.2 W/m²	7.47 MJ
Day 2	618 W/m²	239.8 W/m²	2.29 MJ
Day 3	693 W/m²	327.9 W/m²	4.5 MJ

Thus, the first day is the most irradiated day and the second day the least.

It is observed that all temperatures have the same evolution as the irradiation.

And that the air temperature at the outlet of the solar air heater is higher than the ambient temperature for each day until the next morning. **Table 4** records the values of the maximum and average temperature of ambient air, of the air at the outlet of the solar air heater and of stones. The highest temperatures recorded were for the two most irradiated days. This indicates that the evolution of temperatures depends on the total irradiation received. These values also show that the temperatures of the stones and air at the outlet of the solar air heater are higher than the ambient temperature. The maximum temperature differences between air at the outlet of the solar collector and ambient air are 13.24˚C, 10.19˚C and 16.31˚C for the first day, second day and third day respectively. And the mean maximum temperature difference is 13.25˚C. And the average temperature differences between air at the outlet of the solar air heater and ambient air are 6.98˚C, 4.23˚C, and 6.56˚C for the first, second and third day respectively. And that even at night. These values were before nightfall respectively of 9.78˚C, 6.19˚C, 9.5˚C. These temperature differences can provide the energy needed to carry out the drying process day and night. In addition, the maximum air temperature at the outlet of the solar air heater is below the recommended drying limit temperature of 60˚C [45].

Table 4. Maximum and average temperature values for ambient air, collector outlet air and for stones.

	Ambient temperature		Solar air heater outlet temperature		Stones temperature	
	Maximum value	Average value	Maximum value	Average value	Maximum value	Average value
Day 1	38.94˚C	28.11˚C	52.81˚C	35.09˚C	56.17˚C	35.53˚C
Day 2	31.69˚C	27.13˚C	41.88˚C	31.36˚C	43.05˚C	31.03˚C
Day 3	39.38˚C	28.54˚C	55.69˚C	35.10˚C	59.83˚C	35.82˚C

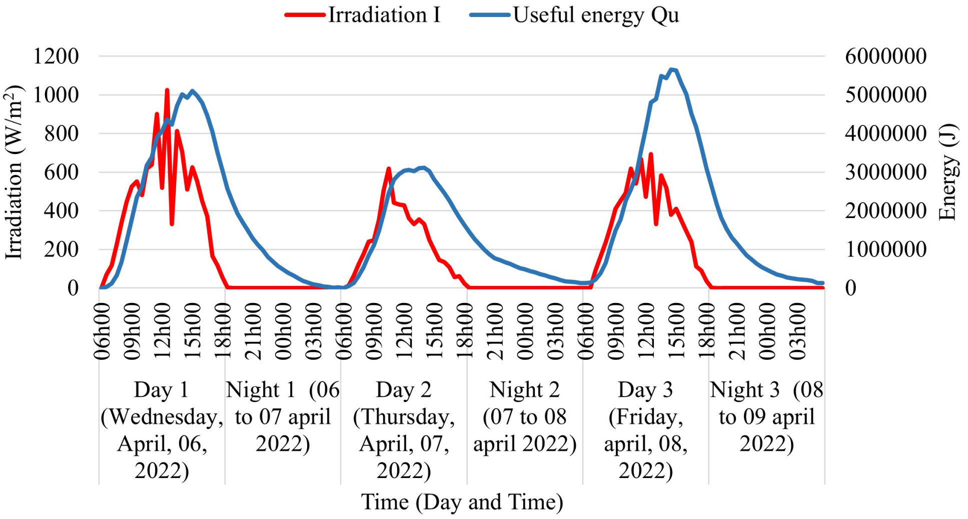

Figure 12. Evolution of the irradiation and useful energy with time.

Figure 12 shows the evolution of the irradiation and useful energy with time. The useful energy, which is the energy, needed for drying is calculated with the following relation:

$$Q_u = m_p C_p \left(T_p(t) - T_{p0} \right) \quad (32)$$

The evolution of useful energy follows that of irradiation. Indeed, like the irradiation, useful energy has two phases in its evolution. An ascending phase and a descending phase. The useful energy ascending phase is explained by the increase of irradiation during this phase. And the decrease of the useful energy is due to the decrease of irradiation. However, it should be noted that although decreasing, the useful energy remains available during the night and is cancelled the next morning at almost 6:00 while the irradiation, it is canceled around 18:00.

The availability of energy even after 6 pm is explained by the fact that part of the energy stored by the stones is used for drying the beans during the day and the other part is stored to continue the drying process at night. This highlights the ability of stones to store heat and the ability of insulating cover to reduce the upwards thermal losses. The maximum and average useful energies are 10.02 MJ and 3.9 MJ for the first day, 6.2 MJ and 2.6 MJ for the second day, 11.06 MJ and 3.8 MJ for the third day.

The average efficiency of the solar air heater is 40%. And that of the drying is 34%. These efficiencies values are acceptable or better than those found in the literature.

Indeed, Vijayan *et al.* [20] reported a thermal efficiency of 22% for the heat collector. Kamble *et al.* [21] reported a drying efficiency of 34%.

Nabnean *et al.* [22] have built a solar dryer with a sensible heat storage system (a water cum TES tank) for drying 100 kg of tomatoes. They successfully dried the 100 kg of tomatoes in 4 days, reducing their moisture content from 62% to 15% in wet basis. They also found an efficiency of the heat collector ranging between 21% and 69%. Amer *et al.* [23] found a thermal drying efficiency of 31.7%.

Reyes *et al.* [24] reported thermal efficiencies ranging from 22% to 67% for the collector and 10% to 21% for the storage unit.

Figure 13 shows the evolution of moisture content when cocoa beans are dried with indirect solar drying and open air drying. This figure shows that the moisture content of beans placed inside the solar dryer and those exposed to ambient air is decreasing with time. According to A.O. Fagunwa *et al.*, a cocoa bean is considered dried when its moisture content is reduced between 6 and 8% in wet basis [27]. Thus we find that the moisture content of beans placed in the dryer goes from 60% to 7% in 35 h, while the moisture content of beans exposed to ambient air goes from 60% to 7% in 61 h. With this dryer the drying time is reduced by 42% compared to natural drying.

As shown in **Figure 14**, the phase of rapid decrease of the reduced moisture content is accompanied by an increase of the drying rate and the decreasing phase is accompanied by a decrease of the drying rate. The main drying steps are observed. This is the heating period which starts from 06:00 to 12:00, the constant speed period which starts from 12:00 to 17:00 and the decreasing speed period which starts from 17:00, until Saturday 09 April 2022 at 18:00.

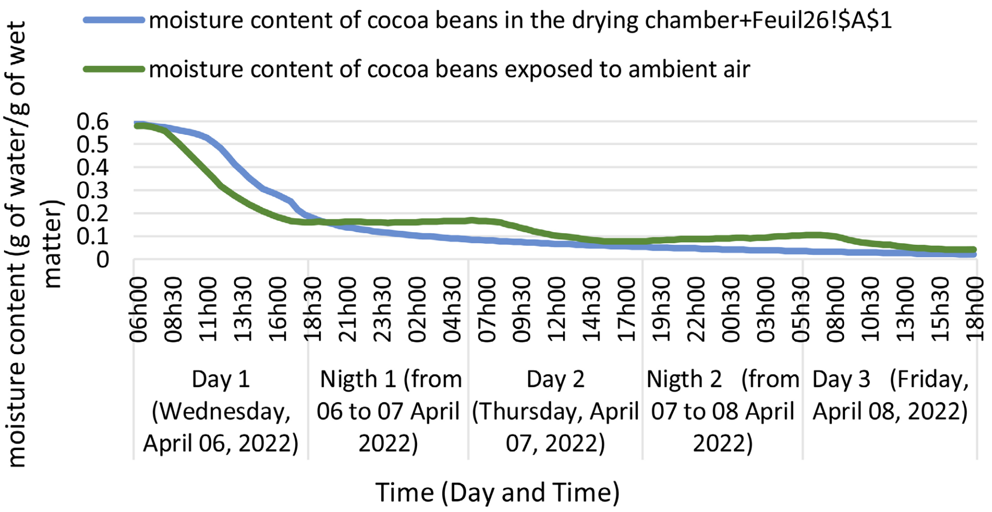

Figure 13. Comparative evolution of the cocoa beans moisture content in the dryer and exposed to ambient air.

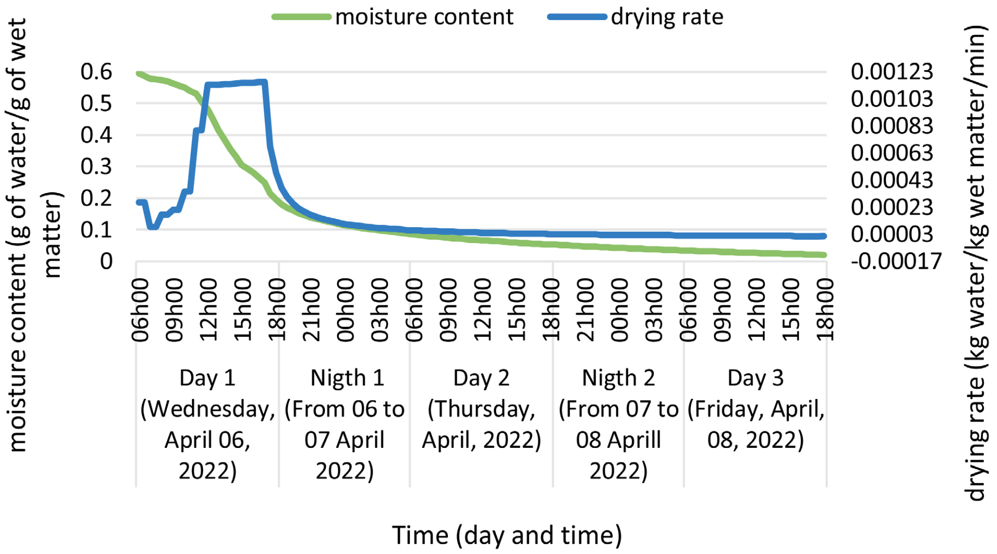

Figure 14. Evolution of moisture content and drying speed with time.

The results of the correlation of the evolution of reduced moisture with time with mathematical models are presented in **Table 5**. All selected models give a good concordance with an $R^2 \geq 0.95$. The models with better agreement with the experimental results are those of Henderson and Pabis, Logaritmic, Two-term model, Verma *et al.*, Midilli, Weibull distribution, Hii and Jena and Denas with $R^2 \geq 0.97$. Only the models of Hii, Jena and Das, Demir *et al.* and Alibas give the best concordances with values of R^2, respectively of 0.9983, 0.9843, 0.9813 and 0.9837.

The equation giving the evolution of the reduced moisture content with the Hii model is given by the following relation:

$$XR = 0.17843061 \cdot \mathrm{e}^{-0.00015634 \cdot t^{2.294364}} + 0.82481183 \cdot \mathrm{e}^{-0.0051688 \cdot t^{2.294364}} \quad (49)$$

Table 5. Results of cocoa beans drying modelling.

Mathematical models	Constantes du modèle	R^2	χ^2	RMSE
Lewis	$k = 0.07311479$	0.9509	0.00281275	0.05287818
Henderson and Pabis	$a = 1.17597135$; $b = 0.08662697$	0.9713	0.00208794	0.04542283
Page	$k = 0.03188941$; $n = 1.31739102$	0.9643	0.00247011	0.0494052
Modified Page	$k = 0.0755$; $n = 1$	0.9502	0.00283112	0.05289254
Logarithmic	$a = 1.17035712$; $k = 0.09345491$; $c = 0.02306248$	0.9748	0.00174306	0.0413778
Two-term model	$a = 0.58798685$; $k_0 = 0.0866273$; $b = 0.58798685$; $k_1 = 0.0866273$	0.9713	0.00211326	0.04542288
Two-term exponential	$a = 0.99834694$; $k_0 = 0.07424965$	0.9508	0.00281998	0.05278837
Verma *et al.*	$a = 1.35113616$; $k = 0.09884781$; $g = 0.66565341$	0.9782	0.00163374	0.04005922
Approximation of diffusion	$a = 7.09390186$; $k_0 = 0.06315839$; $b = 0.97678231$	0.9511	0.00287256	0.05311846
Midilli	$a = 1.11673725$; $k = 0.0518201$; $n = 1.19420338$; $b = 0.00045135$	0.9766	0.00165832	0.0402377
Weibull	$a = 14$; $n = 1$	0.9505	0.00288136	0.05335973
Logit	$a = 19011791.2$; $k = 0.07311572$	0.9509	0.00282957	0.05287804
Hii	$a = 0.17843061$; $k = 0.00015634$; $n = 2.294364$; $c = 0.82481183$; $g = 0.0051688$	0.9983	0.00011806	0.01070368
Weibull distribution	$a = 0.0319$; $b = -1.19999992$; $k = 0.1$; $n = 1.000001$	0.9736	0.00184837	0.04248088
Jenas and Das	$a = 0.89924004$; $k = 0.16086631$ $b = 0.29122838$; $c = 0.03846326$	0.9843	0.00107861	0.03245125
Demir *et al.*	$a = 1.03767354$; $k = 0.03216461$ $n = 1.4072355$; $c = 0.04302404$	0.9813	0.00129236	0.03552145
Alibas	$a = 0.96107361$; $k = 1.23692913$; $n = 1.03549986$; $b = 1.26719461$; $g = 0.04439816$	0.9837	0.0011297	0.03311008
Logistic	$a_0 = 20569083$; $a = 17491108.4$; $k = 0.08662726$	0.9713	0.00210053	0.04542288

7. Conclusions

An indirect solar dryer with a heat storage system was designed and used to dry cocoa beans. The study focused on the evolution of temperature of the heat transfer fluid at the outlet of the solar air heater. The moisture content and the drying speed as a function of time. These results showed that:

- ✓ the moisture content of cocoa beans could be reduced from 60% to 7% in 35 hours. with a reduction in drying time of 42% compared to drying in ambient air;
- ✓ the drying and solar collector efficiencies obtained are 34% and 40%. respectively;
- ✓ the air temperature at the outlet of the solar air heater remains higher than the ambient temperature during day and night;
- ✓ the amount of energy stored by the stones is sufficient to allow continuity of the drying operation day and night;

- ✓ the Hii. Jena and Das. Demir *et al.* and Alibas models give the best concordances with R^2 values of 0.9983. 0.9843. 0.9813 and 0.9837 respectively.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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