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Drying kinetics of cassava by indirect drying in forced convection

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ABSTRACT: The main objective of this study is to estimate the drying parameters of cassava using an indirect solar dryer equipped with a sensible heat energy storage system. This dryer, which uses stones as storage material and made of wood and plywood, was used to dry a quantity of 12.2 kg of cassava. Drying parameters relating to drying curves and drying efficiency of cassava were established and studied. The drying curves were modeled using semi-empirical models. The results showed that the water content of cassava decreased from 159.12 g H_2O / 100 g dry matter to 13.32 g H_2O / 100 g dry matter. With a collector and drying efficiency of 56.64% and 29.39% respectively. The Weibull distribution model allows a satisfactory modeling of the drying curve, with an $r^2 = 0.988$, a $\chi^2 = 0.000896$, and an RMSE = 0.0288.

KEYWORDS: Cassava, indirect solar dryer, heat storage, drying curve, Solar Energy.

1 INTRODUCTION

Most farmers in West Africa are faced with the problem of medium and long term preservation of their agricultural crops. Indeed, many losses caused by the use of inadequate means for the preservation of their agricultural crops are recorded [1]; because these means do not allow reducing the proliferation of micro-organisms responsible for the deterioration of agricultural products [2]. Many agricultural products must go through a drying process after harvesting. Indeed, dried products are better preserved; their water content being low enough, so the micro-organisms responsible for the deterioration of agricultural products cannot proliferate [3].

The most commonly used method for drying agricultural products is traditional drying. Drying consists of exposing the products directly to the sun, on the ground, on stalls, on the roofs of houses for example. Although this method is almost free and simple to implement, it poses a problem of hygiene and lengthening of the drying time. Indeed, this method of drying exposes the product to domestic animals, insects, foreign materials [4], birds and dust, which are obvious causes of diseases and poor quality products. This mode, strongly dependent on the intermittent nature of the sun, does not allow control of the drying time and the drying process [1,3]. To eliminate or reduce the problems caused by traditional drying, many direct, indirect and mixed solar dryers have been designed.

Cassava, which is widely cultivated in West Africa, is one of those agricultural products for which several solar dryers have been designed to limit and reduce the problems encountered by traditional drying [5]. Cassava (Manihot esculenta Crantz) is one of the most important food crops in the humid tropics. The annual production of cassava in Africa represents more than half of the world production, estimated at 256.56 million tons [5]. In Côte d'Ivoire, cassava is mainly produced in the south, west and center. Annual production reaches 2.41 million tons, with a yield of 6.5 tons per hectare [5]. Cassava is widely consumed in Côte d'Ivoire in the form of semolina, commonly called "attiéké" and heavy paste called "placali", gari, foutou, concondé, etc. Given its importance in the diet of Côte d'Ivoire, its proper preservation is a vital necessity. [5]

Several works on different aspects of the drying kinetics of cassava roots such as curves of evolution of water content, drying speed [6 - 11], determination of drying constants are reported in the literature [11]. Thus, Saheeda Mujaffar and Amanda Lalla [12] reported that cassava is considered completely dried when its water content is reduced to the acceptable limit of 16% in dry basis (i.e. 14% in wet basis). Ogheneruona and Jusuf [13] reported that the optimum drying temperature for cassava is 52°C.

As the drying time is strongly dependent on the duration of sunshine and the intermittent nature of the sun [14], the need for thermal storage, associated with a solar air collector, is necessary for continuous drying [15]. Indirect solar dryers using a thermal storage system have been realized and studied. Chauhan et al. [16] studied the drying characteristics of coriander, with a solar air dryer coupled with a thermal storage tank of stone beds. A theoretical study was conducted by writing the equations translating the heat transfers between the different components of the system. The results showed that the stored energy can be efficiently used to dry agricultural products during periods of no sunlight. Tiwari et al. [17], made an experimental study of a solar air dryer with a stone bed thermal storage unit placed in the drying chamber. They concluded on the basis of analytical results that the drying time is significantly reduced compared to natural drying. Mishra and Sharma [18], conducted an experimental study of a single glazed air solar collector with two air veins, one of which is filled with stone beds, using iron and aluminum chips and stones as storage material. They concluded that the system, using iron shavings give better efficiency and air temperature at the outlet of the solar collector. The maximum values of collector efficiency are 32% for the system with iron chips and 27% for the system with stones.

A double-glazed air collector with stone beds and a single air stream has been studied experimentally and theoretically by Hamdan [19]. The study showed that the system has a maximum thermal efficiency of 46%, when tilted by 47° and with a mass flow rate of 0.0102 kg/s. In most of these air collectors with a heat storage unit, there is a flat plate air collector coupled with a storage unit. In these systems, the absorber is placed either above the stone bed or below the stone bed.

An indirect solar dryer with a solar air collector using only black painted stones as absorber and storage material was designed and tested while drying cassava. The study investigated the efficiency of the solar collector and drying process, as well as the time-dependent evolution of the temperatures of the heat transfer fluid at the collector outlet, the stones and the water content of the cassava. This was done during a particularly cloudy period.

2 MATERIALS AND METHODS

2.1 DESCRIPTION OF THE SOLAR DRYER

Figures 1 and 2 show respectively a picture and a detailed diagram of the indirect solar dryer which is made of plywood and wood. It consists of a solar air collector, connected to a drying chamber. The solar air collector is a sensible heat energy storage unit, using black painted stones as absorber and heat storage material. It is 1.88 m long, 0.82 m wide and 0.15 m high. A 5 mm thick glass with a surface area of $1.54\ m^2$ is placed above the heat storage unit to reduce upward heat loss. The 0.15 m between the glass and the bottom of the heat storage unit is filled with stones to store heat and thus maintain a drying temperature above the ambient temperature [20]. The 0.12 m high stone bed rests on a reflector plate to increase the amount of heat reaching the stones and to reduce heat loss downwards. And the distance between the last stone level and the glass is 0.03 m. The storage unit is insulated on its side faces with polystyrene of thickness 0.20 m and thermal conductivity0.047 W.m^{-1}.°C^{-1}. The bottom of the storage unit is also insulated with 0.20 cm thick polystyrene. The solar air collector is tilted at an angle of $10°$, relative to the horizontal [21]. The storage unit has two rectangular openings of 0.12 m high and 0.82 m wide at its inlet and outlet. The storage unit is connected by its outlet opening to a drying chamber. The drying chamber, which is made of plywood of 0.20 m thickness, is 1 m high, 1 m wide and 1 m long. It is designed to receive four (4) racks on which the cassava slices are placed. The trays are 0.10 m apart from each other. Each rack is made of wooden structure with rubber nets of $1\ m^2$ of surface to facilitate the passage of air. The drying chamber has a door on one side through which access is gained in order to introduce or remove the cassava slices to be dried. At the exit of the drying chamber is placed a fan with a power of 4.2 W, to force the air through the stones.

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

The heat transfer fluid, now hot, leaves the solar collector, through the opening at the back of the collector, enters the drying chamber, and crosses the cassava slices, spread out on the racks.

Thus, the heat transfer fluid removes the water contained in the slices. Then the air loaded with the humidity of the cassava slices, leaves the drying chamber through a chimney.

Fig. 1. Photo of the dryer

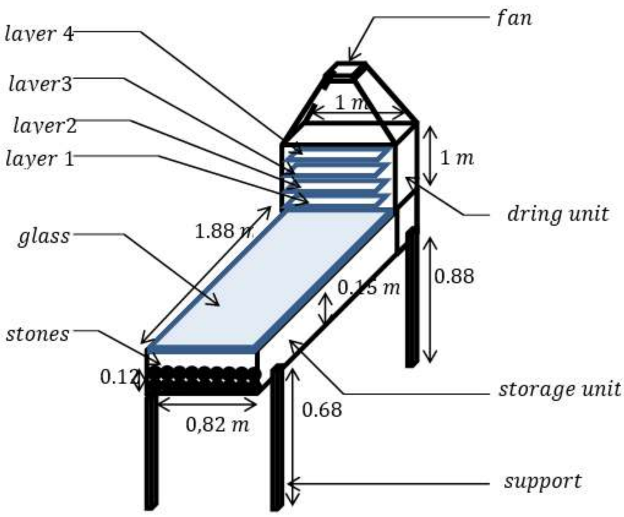

Fig. 2. Schematic of the dryer solaire

2.2 MEASUREMENT EQUIPMENT

The measurement unit consists of:

- Sixteen (16) temperature probes which are 10 KΩ thermistors, i.e. whose resistance has a value of 10 kilo-ohms. The resistance R_{th}, of the thermistor is a function of the temperature T, according to the relationship:

$$R_{th}(T) = R_{th}(T_0)\exp(\beta(\frac{1}{T} + \frac{1}{T_0})) \quad (1)$$

Either,

$$T = \frac{1}{\frac{1}{T_0} + \frac{1}{\beta}\ln[\frac{R_{th}(T)}{R_{th}(T_0)}]} \quad (2)$$

With a precision of 1% from 0 to 100°C. With T_0, the reference temperature taken equal to $298.15°K$ i.e. 25°C; $\beta = 3950\ K; R_{th}(T_0)$: the resistance at the reference temperature, taken equal to 10 kΩ.

- A KIPP ZONEN solarimeter, with sensitivity 0.0049 mv for $1\mathrm{W/m^2}$ and accuracy 0.01 $\mathrm{W/m^2}$; for measurement of illumination.

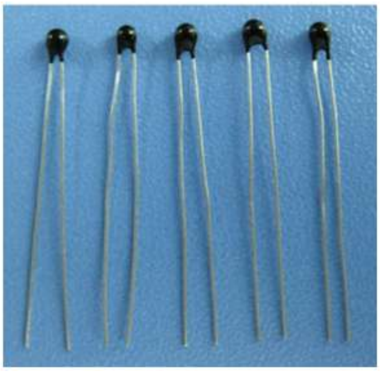

Fig. 3. Thermistance 10 K image

Fig. 4. KIPP ZONEN Solarimeter

- An electronic balance of precision 0.01 g, for the measurement of the mass.

Fig. 5. Electronic balance

Temperature sensors are placed at different locations in the solar dryer to measure temperatures at the stones, the glass, the products on the racks, the air at the inlet and outlet of the stocker and the air at the outlet of the dryer (Figure 6).

Every hour, the temperature values are recorded on a computer, using a data logging system; the cassava slices in the drying chamber are placed on the electronic scale for weighing. And the irradiance value measured by the solarimeter and read on a solar integrator.

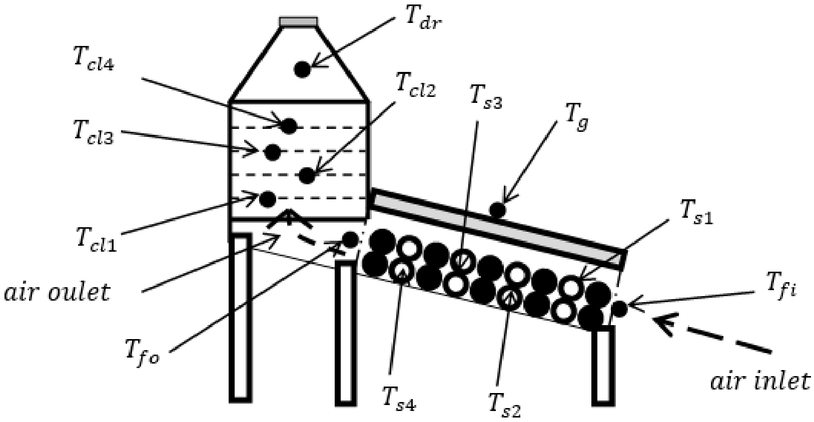

Fig. 6. Position of temperature probes

2.3 EXPERIMENTAL PROCEDURE

The cassava has been peeled, cut into slices, washed, and placed on the drying chamber racks for drying. A quantity of 3.05 kg of cassava is uniformly distributed on each of the drying racks of the solar dryer (figure 7).

Fig. 7. Cassava

2.4 THEORETICAL ANALYSIS

2.4.1 MODELING OF CASSAVA DRYING

Léon et al. [22] proposed a procedure to evaluate the performance of a solar drying system. During the drying process, weighing is done every hour. And using equation (1), we determine the water content of cassava at each time in dry basis X(t).

$$X(t) = \frac{m(t) - m_f}{m_f(t)} x100 \quad (3)$$

With $m(t)$: mass of cassava at time t; m_f: final mass of cassava; $X_w(t)$: water content at time t ;

Thus, the initial water content in wet basis is given by:

$$X_i = \frac{m_i - m_f}{m_f} x100 \tag{4}$$

The mass of water (m_w) to be removed from the product is determined from the initial water content and the desired final water content [23]:

$$m_w = \frac{(X_i - X_f)}{(100 - X_f)} x\, m_i \tag{5}$$

The reduced water content XR is given by:

$$XR = \frac{X(t) - X_e}{X_i - X_e} \tag{6}$$

With m(t): mass at time t; m_i: initial mass; m_f : final mass; m_{ew}: mass of water removed; X(t): water content at time t; X_i: initial water content; X_e : equilibrium water content; XR: reduced water content.

Several studies [24-26] report that the equilibrium water content X_e , is very small compared to the initial water content X_i and the water content at each time t, X(t). Thus in the previous study, the reduced water content will be reduced to the following expression:

$$XR = \frac{X(t)}{X_i} \tag{7}$$

The experimental values of the reduced water content as a function of time will be compared with the non-linear theoretical models of thin film drying to select the model(s) that best describe the thin film drying of cassava. Semi-theoretical models commonly used to describe thin film drying are given in Table 1. To assess the quality of fit with the selected model, three comparison parameters are used. The first is the coefficient of determination (R^2). Next come, the root mean square error (RMSE) and the reduced chi-square (χ^2). The values of these three parameters are obtained from relations 6, 7 and 8 [27, 28].

$$R^2=1-\frac{\sum_{j=1}^{N}\left(XR_{exp,i}-XR_{pre,i}\right)^2}{\sum_{j=1}^{N}\left(\overline{XR}_{exp}-XR_{exp,i}\right)^2} \tag{8}$$

$$RMSE=\left[\frac{\sum_{i=1}^{N}\left(XR_{exp,i}-XR_{pre,i}\right)^2}{N}\right]^{\frac{1}{2}} \tag{9}$$

$$\chi^2=\frac{\sum_{i=1}^{N}\left(XR_{exp,i}-XR_{pre,i}\right)^2}{N-n} \tag{10}$$

With $XR_{exp,i}$:the ith experimental value of the reduced water content ;

$XR_{pre,i}$: the ith predicted value of the reduced water content ; N: the number of observed values; n: the number of constants of the drying model.

Thus, the selected model will be the best fit if the value of R^2 is high and the values of RMSE and χ^2 are low. The curve of the evolution of the reduced water content as a function of time will be modeled using theoretical models presented in Table 1. The modeling of the drying layer may be performed using Curve Expert Professional version 2.7.1 and excel solver software.

Table 1. Mathematical models used to model the drying curves

Model No.	Model name	Model equation	References
1	Lewis	$XR=\exp(-kt)$	Ayansu (1997) [29]
2	Henderson and Pabis	$XR=a\exp(-bt)$	Mahmutoglu et al. (1996)[30]
3	Page	$XR=\exp(-kt^n)$	Basunia and Abe (2001)[31]
4	Modified Page	$XR=\exp[-(kt)^n]$	Togrui and Pehlivan (2002)[32]
5	Logarithmic	$XR=a\exp(-kt)+c$	Yaldiz et al. (2001) [27]
6	Two-term model	$XR=a\exp(-k_0t)+b\exp(-k_1t)$	Lahsasni et al. (2004)[33]
7	Two-term exponential	$XR=a\exp(-k_0t)+(1-a)\exp(-k_0at)$	Midilli and Kucuk (2003) [34]
8	Verma et al.	$XR=a\exp(-kt)+(1-a)\exp(-gt)$	Doymaz (2005) [35]
9	Approximation of diffusion	$XR=a\exp(-k_0t)+(1-a)\exp(-k_0bt)$	Usub et al. (2009)[24]
10	Wang and Singh	$XR=1+a.t+b.t^2$	Usub et al. (2009)[24]
11	Midilli	$XR=a.\exp(-k.t^n)+b.t$	Meisami-asl et al. (2009) [36]; Ojediran and Raji (2010)[37]
12	Weibull	$XR=\exp[-(t/a)^n]$	Meisami-asl et al. (2009) [36]; Ojediran and Raji (2010)[37]
13	Logit	$XR=a/(1+a.\exp(k.t))$	Meisami-asl et al. (2009) [36]; Ojediran and Raji (2010)[37]
14	Hii	$XR=a.\exp(-k.t^n)+c.\exp(-g.t^n)$	Saheeda Mujaffar (2020)[38]
15	Weibull distribution	$XR=a-b.\exp(-k.t^n)$	Saheeda Mujaffar (2020) [38]
16	Jena and Das	$XR=a.\exp(-k.t+b.t^{1/2})+c$	Saheeda Mujaffar (2020) [38]
17	Demir et al.	$XR=a.\exp(-k.t^n)+c$	Saheeda Mujaffar (2020) [38]
18	Alibas	$XR=a.\exp(-k.t^n+b.t)+g$	Saheeda Mujaffar (2020) [38]
19	Logistic	$XR=a_0/(1+a.\exp(k.t))$	Saheeda Mujaffar (2020) [38]

2.4.2 Drying performance

The drying performance of a solar drying system is measured through the efficiency of its solar collector (η_c), and the efficiency of the dryer (η_{dr}). For an indirect solar dryer, the efficiency of the solar air collector is derived from the relation (11) giving the useful power (P_u) supplied by the collector [39]:

$$P_u=\dot{m}_a C_a(T_{fs}-T_{fe}) = \eta_c \times A \times E \tag{11}$$

Then we obtain:

$$\eta_c=\frac{\dot{m}_a C_a(T_{fs}-T_{fe})}{A_P \times E} \tag{12}$$

The drying efficiency gives the overall efficiency of a drying system. The drying efficiency of a forced convection solar dryer is determined from the relation (13) by considering the energy consumed by the fan [24]:

$$\eta_{dr}=\frac{m_{eau}\times L_V}{E\times\Delta t\times A_P+E_F} \tag{13}$$

With $L_V = 2.5018.10^3-2,378\times T_{sh}$ [40] (14)

From relations 12 and 13, we define the instantaneous sensor $\eta_c(t)$ and drying efficiencies $\eta_{dr}(t)$:

$$\eta_c(t)=\frac{\dot{m}_a C_a(T_{fs}-T_{fe})}{A_P\times E(t)} \tag{15}$$

$$\eta_{dr}(t)=\frac{[m_{eau}(t)-m_{eau}(t+\Delta t)]\times L_V}{|E(t+\Delta t)-E(t)|\times\Delta t\times A_P+E_V} \tag{16}$$

With P_u: useful power (W); $\dot{m}_a$: mass flow rate (kg/s); C_a: heat capacity of the air (j.kg^{-1}.°C^{-1}); T_{fo}: air temperature at the outlet of the collector (°C); T_{fe}: air temperature at the inlet of the collector (°C); A: surface area of the glass (m^2); E: illuminance (W/m^2); L_V: latent heat of vaporization of water (j/kg); E_V: energy developed by the fan (J).

With A_C = 1.54 m^2; $\dot{m}_a$ = 0.06 kg/s; C_a=1005 j.kg^{-1}.°C^{-1}.

3 UNCERTAINTIES ANALYSIS

Uncertainty analysis focuses on the measured and calculated parameters.

3.1 UNCERTAINTIES ON MEASURED PARAMETERS

The measured parameters are temperatures. To determine the uncertainties and errors in the temperature measurements, one uses a digital thermometer as described in the previous section. One then proceeds to a series of several measurements using each of the 16 probes and the digital thermometer under the same experimental conditions to determine statistically representative uncertainties that can be calculated. One determines then the relative uncertainty by taking the differences between the measurement obtained by the digital thermometer and that of the probe. This difference is then reported to the digital one. An average of the relative uncertainties is finally made according to the formula:

$$\overline{\left(\frac{\Delta T}{T_{dT}}\right)} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{T_{dT}-T_{PT}}{T_{dT}}\right) \quad (17)$$

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

3.2 UNCERTAINTIES ON CALCULATED PARAMETERS

The error of the experimental results on the basis of the uncertainties in the primary measurements is performed using the Kline and Mc Clintock relationship [41] as reported by Jia et al. [42]

$$\Delta y = \left[\left(\frac{\partial f}{\partial x_1}\right)^2 (\Delta x_1)^2 + \left(\frac{\partial f}{\partial x_2}\right)^2 (\Delta x_2)^2 + \ldots + \left(\frac{\partial f}{\partial x_n}\right)^2 (\Delta x_n)^2\right]^{0.5} \quad (18)$$

where f is the given function of the independent variables, x is one of the variables of the function and Δx is the absolute error associated with the variable. The relative error is shown as:

$$\frac{\Delta y}{y} = \left[\left(\frac{\partial f}{\partial x_1}\right)^2 \left(\frac{\Delta x_1}{y}\right)^2 + \left(\frac{\partial f}{\partial x_2}\right)^2 \left(\frac{\Delta x_2}{y}\right)^2 + \ldots + \left(\frac{\partial f}{\partial x_n}\right)^2 \left(\frac{\Delta x_n}{y}\right)^2\right]^{0.5} \quad (19)$$

The calculated parameters are the temperatures calculated by the model and the mass flow rate and efficiency calculated from the measured parameters. The calculated temperatures by the model are obtained from the heat fluxes and ambient temperature measured by taking into account the uncertainties in the measurements of these two parameters. The analysis of the results indicates an overall accuracy of about $\pm 2\%$. By the same method, one determines, according to the temperatures, the overall accuracy of the solar collector efficiency as $\pm 0.4\%$ and $\pm 1.1\%$ for the drying efficiency.

4 RESULTS AND DISCUSSIONS

The cassava drying operation took place during the rainy season from Tuesday 24 August 2021 at 07:40 to Friday 27 August 2021 at 22:40, at the site of the Institut National Félix Houphouët Boigny in Yamoussoukro, located between 6°15 and 7°35 north latitude and between 4°40 and 5°40 west longitude.

The parameters measured during this drying operation were the temperatures at the level of the stones, the glass, the ambient air, the air at the entry and exit of the stocker and the mass of the cassava slices. The measurement of these parameters allowed the drawing of the curves represented in figures 8 to 15.

Figures 8, 9, 10 and 11 show the evolution as a function of time of the illuminance, the ambient temperature, the air temperature at the exit of the sensor and the average temperature of the stones respectively for the days of Tuesday 24, Wednesday 25, Thursday 26 and Friday 27 August 2021. Figures 12 and 15 show the time-dependent evolution of water content and reduced water content of cassava, respectively. All these curves are for the period from Tuesday 24 at 07H40 to Friday 27 August 2021 at 22H40, characterized by a total irradiation of 5750 Wh/m^2 .

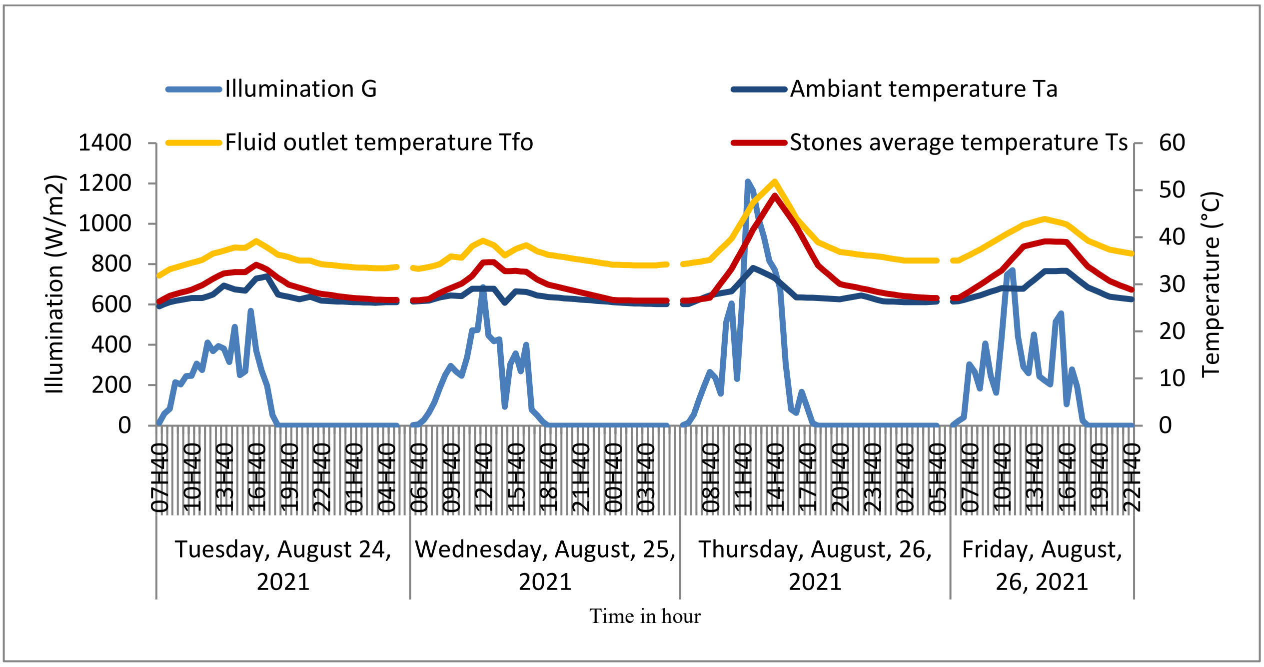

Fig. 8. Evolution of the solar radiation, the ambient temperature, the outlet air temperature and the average temperature of the stones according to the time from Tuesday 24 to Friday 27 August 2021

Analysis of the Figure 8 indicates that the maximum value attained by the solar radiation over the entire drying period is 1163 W/m^2 on Thursday, August 26 at 12:40 PM, with an average value of 313.41 W/m^2. The maximum value reached by the ambient temperature is 31.32°C on Friday, August 27, 2021 at 16H40 with an average value of 27.9°C. It should be noted that the total solar radiation received by the collector for the days of Tuesday, Wednesday, Thursday and Friday are respectively 964 Wh/m^2, 1140 Wh/m^2, 1797 Wh/m^2 and 1849 Wh/m^2. These average values of the solar radiation and ambient temperature, added to that of total solar radiation over the entire drying period are consistent with the cloudy weather observed during this period. It should be noted that from the first day of the drying process, it started to rain. Indeed, this day of August 24, 2021 is characterized by an average ambient temperature of 27.89°C and an average irradiance of 290.22 W/m^2.

These figures also reveal that the air temperature at the outlet of the storage unit is largely above the ambient temperature throughout the drying process with an average difference of about 9°C. And this even in periods of no sunlight. This is due to the ability of the stones to store heat. This difference gives a good indication of the thermal efficiency of the storage unit. Nwofe [1] has reported a maximum temperature difference of about 13°C between the air temperature at the outlet of the solar collector and the ambient temperature. This was done in a comparative study of the drying efficiency of cassava and plantain.

The curve observed in Figure 9 shows that the water content that was initially 160 (g water)⁄(100 g dry basis) at 07H40 on day one increased to 13.32 g water/100 g dry matter on day four at 22H40. However, it should be noted that the recommended water content to consider cassava dry is around 14 g water/g dry basis [43].

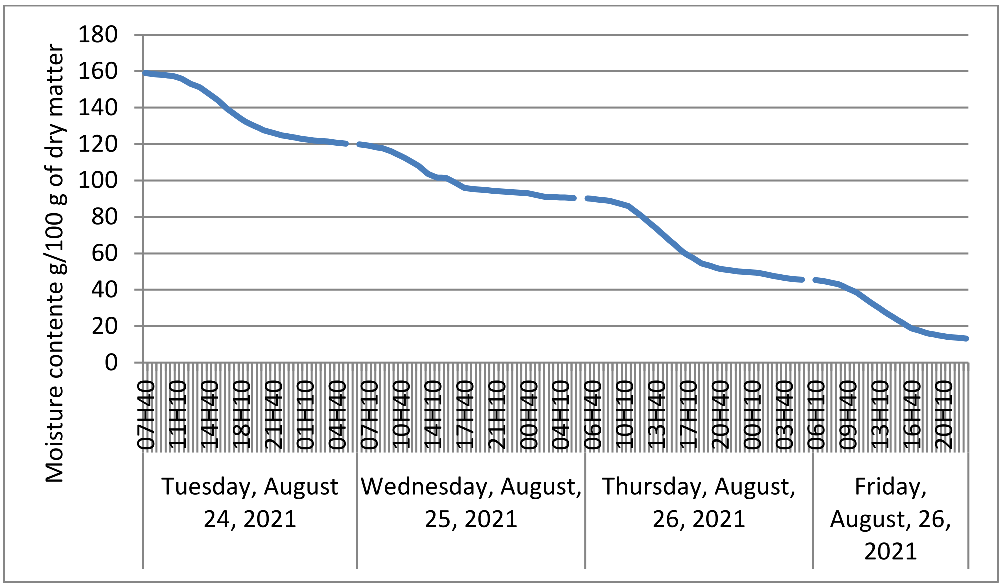

Fig. 9. Evolution of the water content of cassava according to the time from Tuesday, August 24 to Friday, August 27, 2021

This drying time is better than that obtained by Nwofe [1], who in his work on the comparative study of the drying efficiency of cassava and plantain, obtained a drying time of 18 days. Olufayo and Ogunkunle [44] reported a drying time of 16 days with a final moisture content of 15.2 g water/g wet basis. This improvement in drying time can be explained by the fact that the stones used as storage material allow continuous drying of cassava.

Figures 10 and 11 show the time-dependent curves of the solar collector and drying efficiency, respectively. These curves were obtained from relationships (15) and (16).

These curves show that the efficiency of the collector varies between 21.2% and 95.7% with an average value of 56.64% and the drying efficiency varies between 4.01% and 83.69%, with an average value of 24.39%.

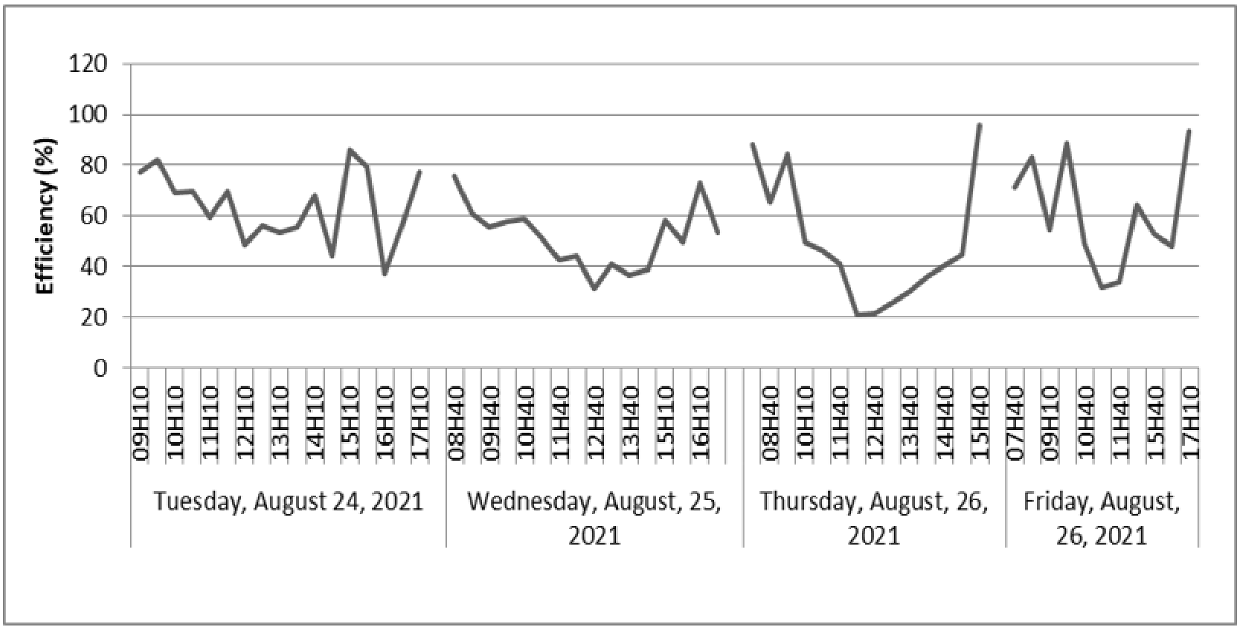

Fig. 10. Evolution of the solar collector efficiency according to the time from Tuesday 24 to Friday 27 August 2021

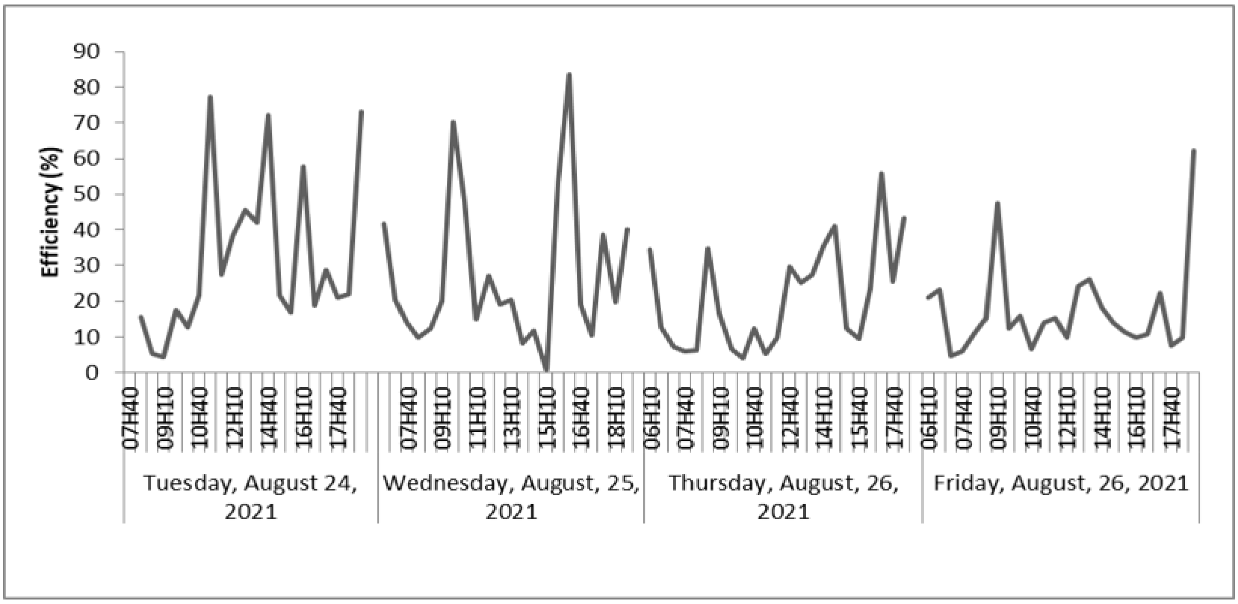

Fig. 11. Evolution of the solar collector efficiency according to the time from Tuesday 24 to Friday 27 August 2021

These values are acceptable or even better than those found in the literature. Indeed, Mohanraj and Chandrasekar [20], analyzed the performance of an indirect solar dryer operating in forced convection to dry copra in India. This solar dryer included a heat storage unit, with sand as the sensible heat storage material. The drying efficiency of this dryer was 24%. Potdukhe and Yhombre [45] conducted a study on an indirect solar dryer with a heat storage system placed under the absorber to improve the drying time for chilli. The drying efficiency was between 8.35 and 21%. Chaouch et al. [46] designed, constructed and analyzed an indirect solar dryer using stones as storage material. This dryer was used for drying camel meat. The drying efficiency was estimated to be 18.34% in July and 15.52% in November. Shanmugam and Natarajan [47] constructed and tested an indirect solar dryer with a heat storage unit using a desiccant as storage material, placed on top of the dryer. The performance of this dryer was studied by drying pineapple. They found a drying efficiency between 20 and 60%. Vlachos et al. [48] used 125 liters of water for heat storage, kept in sealed metal boxes and placed under the drying chamber. The drying efficiency of their system is estimated at 45%. El-Sebaii et al. [49] designed and experimented with a double-glazed air-source solar collector with a storage unit using a gravel bed as storage material. They obtained collector efficiency 22-27% higher than a solar collector without storage unit. Vijayan et al. [50], designed an indirect solar dryer with a heat storage unit, installed under an absorber plate, with forced convection, for drying okra slices. Their study focused on the effect of the storage system and the air mass flow rate on the system performance. They obtained an average drying efficiency of 19% and 22% for the collector.

In Figure 12, we observe a decay of the reduced water content with time. The results of the agreement of the evolution of the reduced water content with time with the mathematical models are presented in Table 2. For all the selected models we obtain an $R^2 \geq 0{,}934.$ The Logarithmic, Wangh and Singh, Midilli, Weibull distribution, Jenas and Jas, Demir et al. and Alibas models give an $R^2 \geq 0.986$. The model with better agreement with the experimental results is the Weibull distribution with an $R^2 = 0.9882$, a $\chi^2 = 0.000896522$, and an $RMSE = 0.028789921$.

Table 2. Results of drying mathematical modelling

Mathematical models	Model constants	R^2	χ^2	RMSE
Lewis	$k = 0{,}016163197510514$	0,934033845	0,004744368	0,068226472
Henderson and Pabis	$a = 1{,}06650702327072$ $b = 0{,}0177749055075141$	0,944886759	0,004041535	0,062362039
Page	$k = 0{,}00402491892911302$ $n = 1{,}35836559741309$	0,96576662	0,002510384	0,049149287
Modified Page	$k = 0{,}01599999998$ $n = 1$	0,933902102	0,004847056	0,068294567
Logarithmic	$a = 43{,}6837022331795$ $k = 0{,}000235725074964372$ $c = -42{,}7001874612136$	0,985945256	0,001051268	0,031492258
Two-term model	$a = 0{,}548964797502381$ $k0 = 0{,}017775044$ $b = 0{,}517545087283951$ $k1 = 0{,}0177749471674923$	0,944886759	0,004206495	0,062362039
Two-term exponential	$a = 1{,}84260768298822$ $k0 = 0{,}0251832902561573$	0,963691044	0,002662589	0,050617328
Verma et al.	$a = 22{,}119545364913$ $k = 0{,}0320564407242344$ $g = 0{,}0332179546625558$	0,965328644	0,002593351	0,049462692
Approximation of diffusion	$a = 1$ $k0 = 0{,}016163188516917$ $b = 1$	0,934033845	0,004934143	0,068226472
Wangh and Singh	$a = -0{,}0108319408435193$ $b = 0{,}0000481826014742986$	0,984901653	0,001107184	0,032640517
Midilli	$a = 1{,}00274901250428$ $k = 0{,}0154783799214545$ $n = 0{,}171711713293958$ $b = -0{,}0100319653516805$	0,986186519	0,001054308	0,03122079
Weibull *	$a = 57{,}98606004513066$ $n = 1{,}358376416143081$	0,965766620	0,005208613	0,07079592
Logit	$a = 2{,}64010376576307.10^8$ $k = 0{,}0161631974419034$	0,934033844	0,004837395	0,068226473
Hii	$a = 0{,}463514398454454$ $k = 0{,}001086972811156$ $n = 1{,}65922747098345$ $c = 0{,}465530676121883$ $g = 0{,}00108698484724706$	0,972191371	0,0021667	0,044297797
Weibull distribution	$a = 1{,}32832254358528$ $b = 0{,}311914721112263$ $k = -0{,}0957782875682518$ $n = 0{,}599128356908698$	0,98825383	0,000896522	0,028789921
Jenas and Jas	$a = 41{,}0762571951307$ $k = 0{,}000244987406491206$ $b = -0{,}0000671884317627618$ $c = -40{,}0860798036555$	0,985965311	0,001071192	0,031469782
Demir et al.	$a = 37{,}8885348523676$ $k = 0{,}000248903360957899$ $n = 1{,}0194250684035$ $c = -36{,}9101637666717$	0,985965146	0,001071204	0,031469967
Alibas	$a = 41{,}1182932646483$ $k = 0{,}00709215104559641$ $n = 1{,}00057952571055$ $b = 0{,}00686051507919621$ $g = -40{,}01393080034813$	0,9859689	0,001093229	0,031465757
Logistic	$a0 = 1{,}12856899297442$ $a = 0{,}189787154654191$ $k = 0{,}0407237983998204$	0,976181512	0,00185581	0,040996749

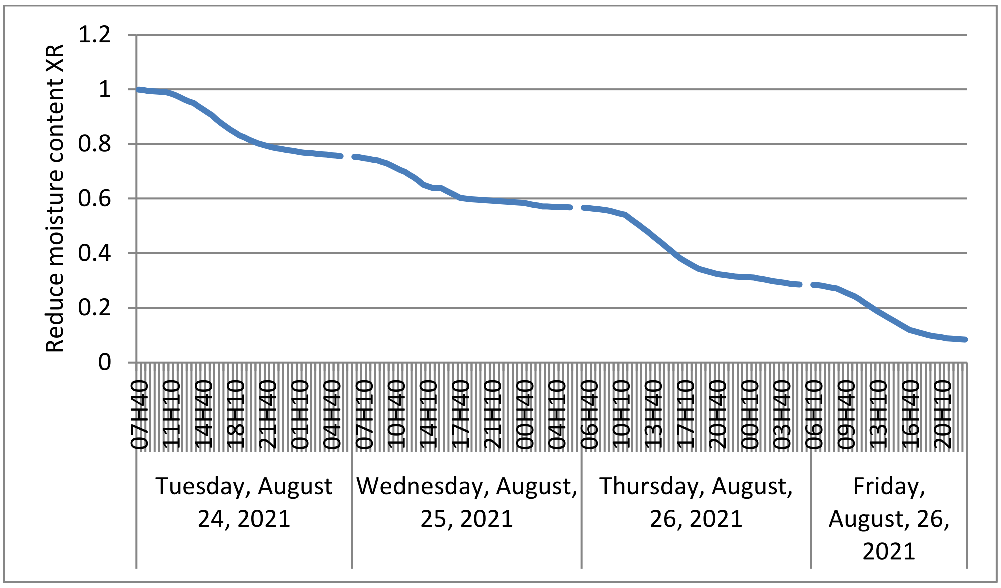

Fig. 12. ***Evolution of the reduce moisturer content of cassava according to the time from Tuesday, August 24 to Friday, August 27, 2021***

The equation giving the evolution of the reduced water content with the Weibull distribution model is given by the following relation:

$$XR=1,328 -0,312.exp(0,096.t^{0,599}) \quad (20)$$

In order to confirm the good agreement obtained with the Weibull distribution model, the theoretical and experimental values of the reduced water content are compared (Figure 13). The plot of the theoretical reduced water content versus the experimental reduced water content gives us a straight line with a directing coefficient of 0.998, very close to the value 1. This confirms the good agreement of the Weibull distribution model with the experimental values of reduced water content.

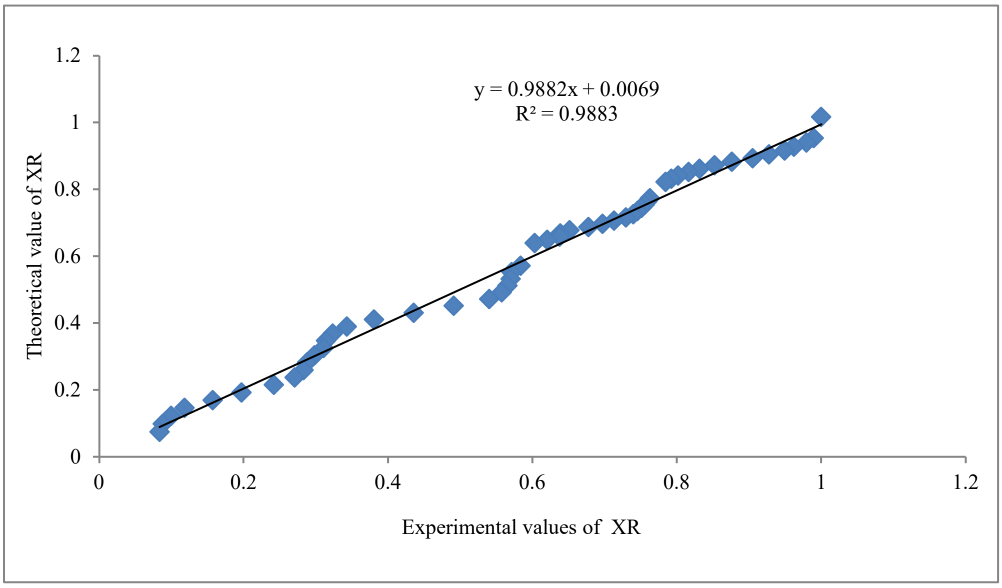

Fig. 13. ***Plot of theoretical reduced water content versus experimental water content from Tuesday, August 24 to Friday, August 27, 2021***

5 CONCLUSION

An indirect solar dryer with a heat storage system was designed and used to dry cassava in cloudy weather. The study focused on the evolution of the temperature of the heat transfer fluid at the outlet of the storage system, the water content and the drying rate as a function of time. These results showed that although the drying temperature was below the recommended temperature for drying cassava due to climatic conditions, the water content of cassava could be reduced to 13.32 g H_2O/100 g dry matter (i.e. 11.75 g H_2O/100 g wet matter) after

3 days and 15 hr of drying, with a drying efficiency and solar collector efficiency of 24.39% and 56.64% respectively. The Weibull distribution model is the one that best agrees with the experimental results with a value of R^2, the highest and values of χ^2 and RMSE, the lowest.

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