

Research Article

Experimental Study of a Mixed Solar Dryer: Application to Drying Okra

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Abstract

Large-scale agricultural production generally occurs during specific periods of the year. This results in the unavailability of products outside of their production periods. Due to their high water content, most agri-food products deteriorate very quickly under the effect of heat, hence the need to develop preservation techniques. Preservation techniques for fresh produce require energy. Burkina Faso is a country with strong solar potential, which is why solar dryers are the most developed technologies for preserving agri-food products. However, the quality of the dried product depends on the quality of the dryer. Our work focuses on the construction of a mixed solar dryer for drying agricultural products. The flat-plate collector is equipped with baffles that allow for greater heat exchange between the air and the hot parts (absorber and baffles) of the collector. The drying chamber is fitted with double-sloped glazing on the roof. An experimental study of hygrothermal parameters, such as air temperature at the racks, product temperature, product water content, and relative humidity inside the drying chamber, was conducted to determine the dryer's performance. We also determined the effective diffusion coefficient and efficiency. The evolution of solar irradiation was monitored during drying operations. Experiments show that the temperature inside the dryer can reach 80 °C to 100 °C. The effective diffusion coefficient is approximately $1.89 \cdot 10^{-7} \text{ m}^2/\text{s}$, and the dryer's efficiency is 28.56%.

Keywords

Mixed Solar Dryer, Okra, Drying Kinetics, Temperature, Efficiency

1. Introduction

Burkina Faso is a country with a pre-Saharan climate, with a rainy season lasting approximately four months and a dry season lasting eight months. Agricultural production, being generally seasonal, influences its availability and cost during the dry season. Thus, the preservation of products with high

moisture content is a problem that must be resolved to make these products available during the dry season. Open-air drying has been a preservation method for years, but it has drawbacks in terms of the quality of the dried product and a relatively long drying time (a few days). This problem can be addressed by

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Received: 16 July 2025; **Accepted:** 20 August 2025; **Published:** 11 September 2025



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proposing a solar dryer that uses solar radiation to generate the energy needed for drying. Thanks to the strong sunshine our country enjoys, solar dryers have been developed. These dryers are of several types and are classified according to the way in which solar radiation reaches the product. In the literature, several authors, such as Diemuodeke E et al., Eke Ben et al., Atul Sharma et al., Bayopo S et al. and Tefera A et al, have carried out studies on the performance of different forms of solar dryers where the products are exposed to solar radiation [1-5]. The results show that they have quite poor performance. Other authors such as Dianda Boureima et al., Thierry Sikoudouin et al., Esakkimuthu et al., V. Shanmugam et al., S. Shanmugam et al., and P. N. Sarsavadia et al., have presented studies on indirect solar dryers where the products are not directly exposed to radiation [6-11]. However, indirect dryers have reduced performance on days of low sunshine. To increase solar irradiation on the dryers, researchers have combined the indirect dryer with the direct dryer. Researchers have developed and conducted studies on several types of indirect dryers. F. K. Forson et al. developed a satisfactory numerical model to predict the performance of a mixed solar dryer [12]. Bukola O. Bolaji et al. In their study, they obtained a drying speed and collector efficiency of 0.62 kg/h and 57.5% respectively [13]. López-Vidaña Erick César et al., developed and evaluated a mixed passive solar dryer. The efficiency of the dryer is estimated at approximately 10.66% [14]. Ahmed Djebli et al., presented the results of an experimental and thermodynamic study of tomato drying in a mixed dryer. Gibbs free energy values indicate that solar drying of tomatoes is a spontaneous natural process [15].

Ikechukwu Celestine Ugwuoke et al. developed and tested a mixed solar dryer for drying several agri-food products. They found that the dryer allowed rapid drying of their products [16]. Chandrakumar B Pardhi et al., after developing a mixed solar dryer, carried out tests on it. The results show that the drying rate, collector efficiency and percentage of moisture removed (on a dry basis) for grape drying were 0.38 kg/h, 67.5% and 85.4% respectively [17]. All these studies have shown the interest of mixed solar dryers. In most of these works, the part exposed to the sun is on a single slope.

Our work consists of carrying out and experimentally studying the performance of a mixed dryer whose direct sun exposure surface is double slope and the flat collector equipped with baffles. The work consisted of determining the temperatures of the different parts of the dryer, determining the drying kinetics of dried okra in the dryer, evaluating the diffusion coefficient of water in the product and the yield.

2. Materials and Methods

2.1. Materials

2.1.1. The Flat-plate

It consists of a 2 mm thick galvanized sheet metal absorber

painted matte black, topped with rectangular obstacles (baffles). The entire assembly is covered with a 5 mm thick clear glass pane. The side and bottom surfaces are thermally insulated with polystyrene. Air circulates between the glass and the absorber to be heated and then flows into the drying chamber. The collector is inclined at an angle of 15° to the horizontal plane and permanently oriented towards the south.

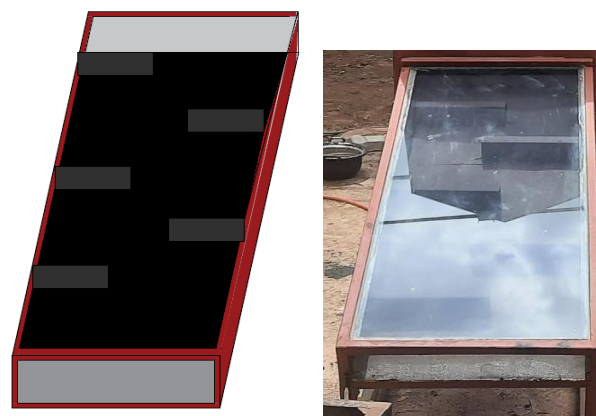


Figure 1. flat panel sensor (equipped with baffle).

2.1.2. The Drying Chamber

The drying chamber is a trapezoidal box. The walls are made of aluminum-zinc sheet metal and insulated with polystyrene and then redwood plywood. The entire structure is clad in aluminum-zinc sheet metal to resist humidity. The upper part is glazed to allow sunlight to penetrate the chamber. The entire structure is topped with a chimney that facilitates the evacuation of humid drying air. The drying chamber contains four galvanized wire racks where the products to be dried are displayed. The racks are numbered from bottom to top, from 1 to 4.

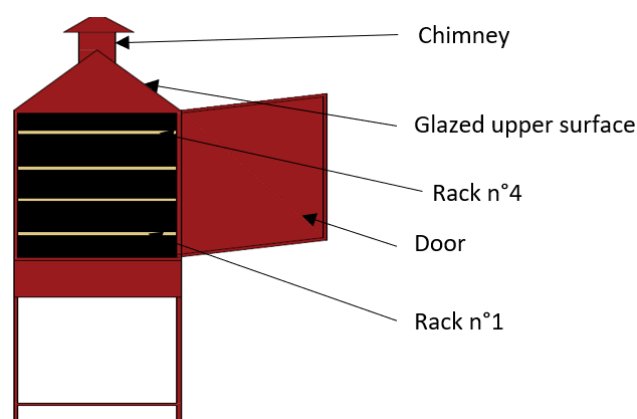


Figure 2. Schematic of the drying chamber.

2.1.3. The Mixed Solar Dryer

The two units, namely the baffle plate collector and the

drying cage, are connected to form the combined solar dryer.



Figure 3. Mixed solar dryer.

2.1.4. Measuring Devices

The various temperatures were measured using K-type thermocouples connected to a GRAPHTEC Midi LOGGER GL 220 data logger. The data logger has a measurement error of $\pm 0.05\%$ of the measured value and is used for temperatures ranging from $-100\text{ }^{\circ}\text{C}$ to $1370\text{ }^{\circ}\text{C}$.

Solar irradiation was measured using a solarimeter. It has a sensitivity of $72\text{ mV}/1000\text{ W}\cdot\text{m}^{-2}$. A hygrometer was used to measure the relative humidity (RH) in the drying chamber. This device has a measurement range of 0 to 100% humidity with a resolution of 0.1% RH and a measurement error of $\pm 3\%$ for a range of 20% to 80% and $\pm 5\%$ for values below 20% RH and above 80% RH.

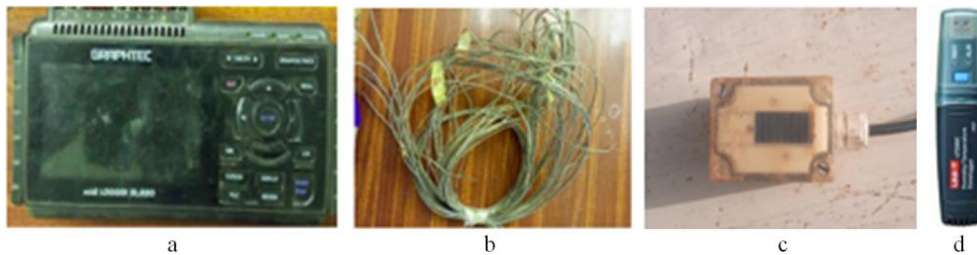


Figure 4. Measuring devices (a: GL220 datalogger, b: thermocouples, c: solarimeter, d: hygrometer).

2.2. Methods

2.2.1. Experimental Protocol

The fresh okra used for drying was washed, drained, and cut into cylindrical shapes. It was then weighed and placed on the drying racks. The sensor and drying chamber were first cleaned.

Thermocouples were placed in the drying chamber (at the inlet, on the racks, and on the products) and in the ambient air. A hygrometer was placed in the drying chamber to monitor the relative humidity of the drying air. A solarimeter recorded the solar irradiation reaching the site. The okra was regularly weighed until a nearly constant mass was obtained, at which point drying was stopped.

2.2.2. Theoretical Approach

The water content at each time was determined by equation (1):

$$X(t) = \frac{m(t) - m_s}{m_s} \quad (1)$$

With:

$X(t)$: the water content at time t ;

$m(t)$: the mass at time t ;

m_s : dry mass

The overall efficiency of the dryer is calculated from

equation (2):

$$\eta_s = \frac{M_v \times L_v}{G_n \times A \times t_s} \quad (2)$$

With:

M_v : mass of water evaporated during the total drying time in kg;

L_v : latent heat of vaporization in J/kg;

G_n : average daily solar radiation on the dryer surface in W/m^2 ;

A : area of the absorber exposed to solar radiation in m^2 ;

t_s : drying time in s.

The diffusion coefficient D_{eff} ($\text{m}^2\cdot\text{s}^{-1}$) is determined by equation (3):

$$X^* = \frac{4}{\alpha_0^2} \exp \left[-(\alpha_0)^2 \times \frac{D_{\text{eff}} \times t}{r^2} \right] \quad (3)$$

With:

X^* : reduced water content;

r : product radius (m);

α_0 : Bessel function of order 0;

t : time (s);

D_{eff} : diffusion coefficient ($\text{m}^2\cdot\text{s}^{-1}$)

3. Results

We conducted trials of the okra drying process using our

mixed solar dryer to determine its performance. The trials were conducted during September 2023, and the results are presented as follows.

3.1. Irradiation Solaire

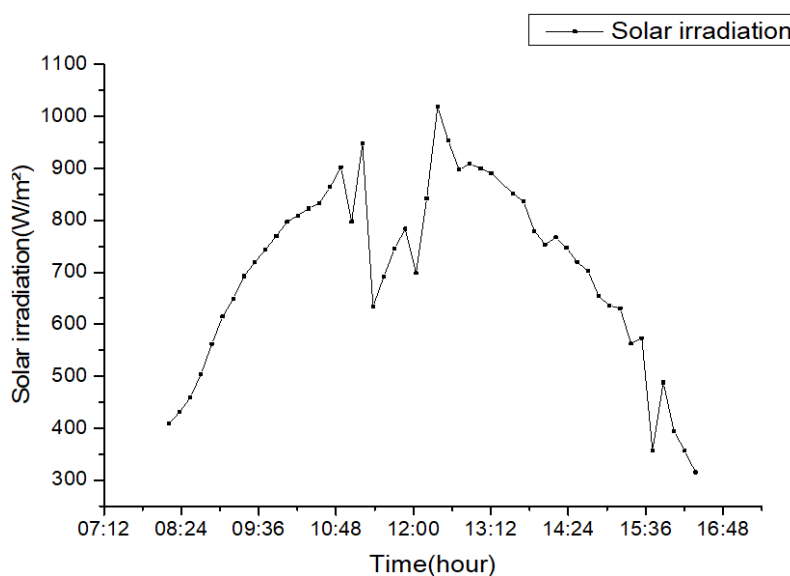


Figure 5. Evolution of solar irradiation.

Observation of the solar irradiation curve reveals a general bell-shaped trend. However, fluctuations are notable, mainly due to cloudy periods, resulting in sudden drops in sunshine. These observations highlight the impact of variable weather

conditions. The maximum solar irradiation is recorded at around 12h22min and is worth 1018 W/m^2 . This value indicates a very sunny day.

3.2. Relative Humidity of the Air

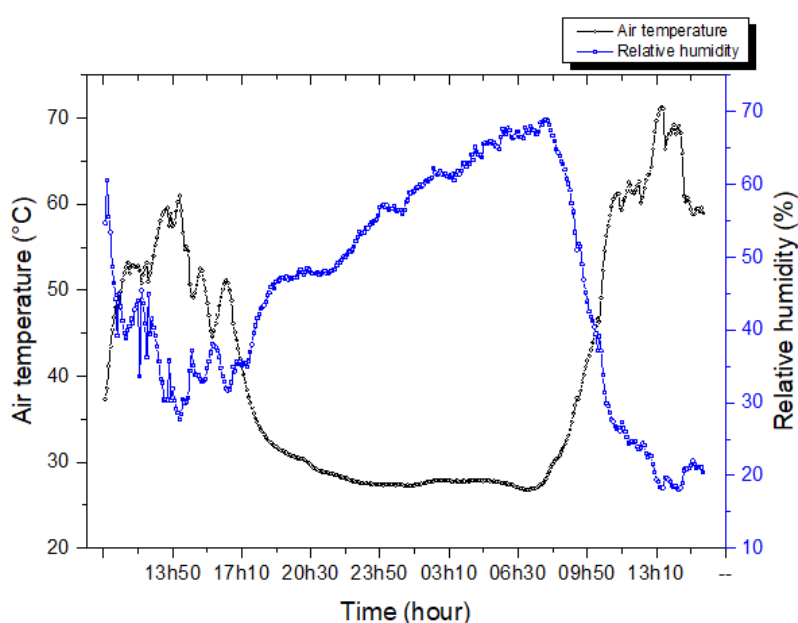


Figure 6. Relative humidity and temperature of drying air.

It can be seen that during the two days of drying, the relative humidity has an opposite evolution to that of the temperature. In other words, when the air temperature in the rack room increases, the relative humidity decreases, and vice versa. The maximum values reached by the air are approximately 60 °C and 70 °C. These maximum temperature values correspond to minimum values of relative humidity which are approximately 35% and 20%. The increase in temperature promotes the evaporation of the moisture present in the air and vice versa. The air thus becomes capable of containing a greater quantity of water vapor, in this case that of the prod-

ucts to be dried. On the other hand, when the temperature inside the room decreases, this reduces the capacity of the air to contain water vapor, which leads to an increase in the relative humidity of the air inside the rack room. A previous study in another indirect solar dryer gives a similar result [18].

3.3. Product and Drying Air Temperatures

Figures 7 and 8 show the changes in the temperatures of the drying air around racks 1 and 4 as well as the temperatures of the products placed on these racks.

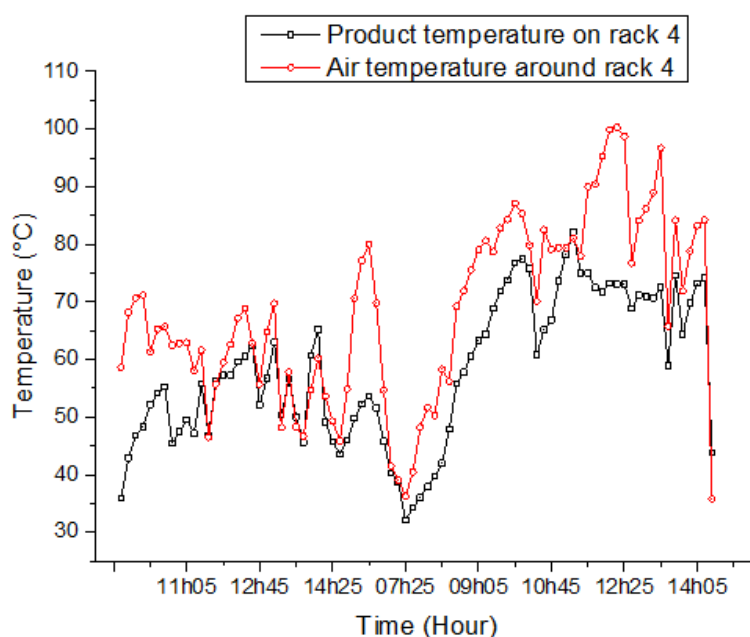


Figure 7. Changes in the temperatures of the drying air and the product on the rack1.

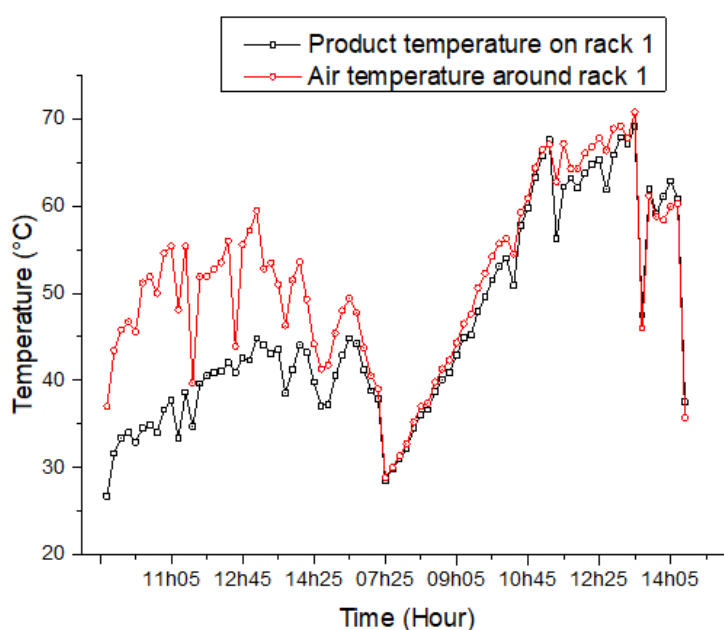


Figure 8. Changes in the temperatures of the drying air and the product on rack 4.

These curves represent the values measured during the two drying days. We first note that the drying air temperatures around rack 4 are higher than those around rack 1. This is explained by the fact that rack 4 is located under the greenhouse placed above the dryer. The air temperatures around rack 1 and rack 4 reached maximum values of 60 °C and 80 °C respectively on the first day and maximum values of 70 °C and 100 °C on the second day. These high temperatures are directly

influenced by the good sunshine on these days. In each of these figures, we see a change in the product temperature similar to that of the drying air temperature. The product temperature increases with that of the drying air and tends towards the latter. This is explained by the fact that hot air serves to evaporate the water from the product and at the same time increase the temperature of the product. Such a result has also been presented in the literature [19, 20].

3.4. Drying Kinetics

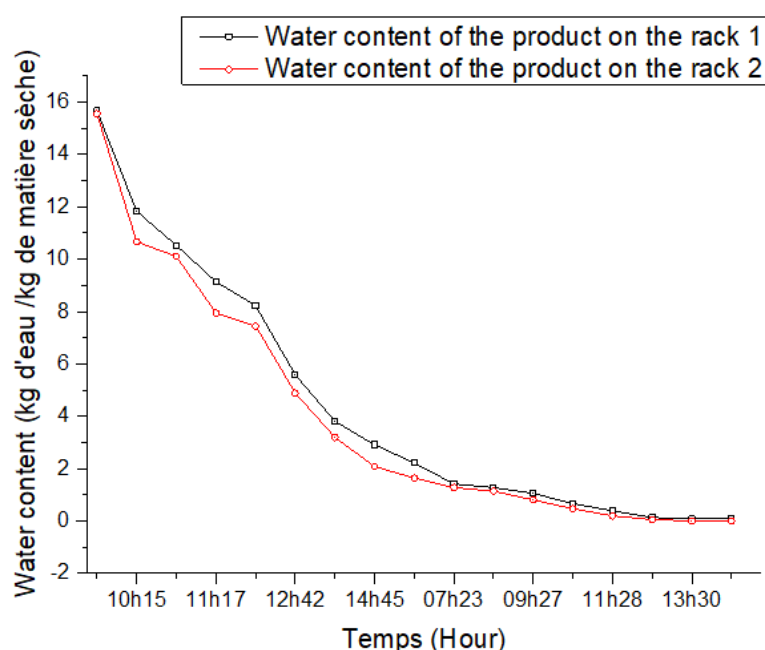


Figure 9. Okra drying kinetics.

Figure 9 shows that the drying of the products placed on rack 4 is a little faster compared to that of rack 1. This is explained by the high temperature of the drying air around rack 4. We also observe overall a single drying phase, namely the decay phase. There is first a rapid decrease until the end of the first day of drying (15: 46), then a slow decrease for the rest of the drying. At the beginning of the process, when the okra is still relatively wet, the moisture is more concentrated on the surface of the products, which promotes rapid evaporation. However, as drying progresses and the amount of moisture on the surface of the products decreases, evaporation becomes increasingly slow. The majority of authors in the literature reach the same result for agri-food products [18, 21-25]. The drying time was 11 hours.

3.5. Effective Diffusion Coefficient of Okra

The representation $\ln(X^*) = f(t)$ allows us to obtain a straight line, and from this line we deduce the effective diffusion coefficient. Its determined value is $1.89 \cdot 10^{-7} \text{ m}^2/\text{s}$.

This value is higher than those obtained by some authors during okra drying [23, 25-28]. This could be due to the high temperature of the drying air.

3.6. Efficiency

The efficiency of the dryer calculated using equation (3) is 28.56%. This means that 28.56% of the incident solar energy is used for drying the products through our mixed solar dryer. Lakshmi et al obtained an efficiency of 12% with their mixed solar dryer [29]. López-Vidaña Erick César et al, obtained an efficiency of 10.66% [14]. Arslan Afzal et al., in their study concluded that their dryer has an efficiency of 33% [24]. Considering the efficiencies in the literature we can say that our dryer has a good efficiency.

4. Conclusion

The study of the mixed solar dryer with a double-sloped glass top showed very high temperatures in the drying cage.

These temperatures can allow the drying of other products requiring sufficient heat. The temperature of the okra subjected to drying reaches temperatures of approximately 80 °C with an effective diffusion coefficient of $1.89 \cdot 10^{-7} \text{ m}^2/\text{s}$. The estimated efficiency is 28.56%. However, regulation of the drying air temperature is necessary for some products whose drying temperatures are of the order of 50 °C or less.

Abbreviations

$X(t)$	Water Content at Time $t(\text{s})$
$m(t)$	Mass at Time $t(\text{s})$
m_s	Dry Mass (kg)
η_s	Overall Efficiency of the Dryer
M_v	Mass of Water Evaporated During the Total Drying Time (kg)
L_v	Latent Heat of Vaporization in (J/kg)
G_n	Average Daily Solar Radiation on the Dryer Surface (W/m^2)
A	Area of the Absorber Exposed to solar Radiation (m^2)
t_s	Drying Time (s)
D_{eff}	Diffusion Coefficient ($\text{m}^2 \cdot \text{s}^{-1}$)
X^*	Reduced Water Content
r	Product Radius (m)
α_0	Bessel Function of Order 0
t	Time (s)

Author Contributions

Dianda Boureima: Conceptualization, Validation
Ouédraogo Germain Wende Pouré Methodology
Aoué Satiatou: Data curation, Funding acquisition
Kam Sié Validation
Bathié Dieudonné Joseph: Validation

Conflicts of Interest

The authors declare no conflicts of interest.

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