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Experimental Study of the Thermal Performance of An Indirect Solar Dryer with Unglazed Collectors Equipped with Three Parabolic Trough Reflectors

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Abstract The preservation of agri-food products is a major challenge in reducing post-harvest losses, which are a major cause of food insecurity worldwide. Drying is an effective preservation technique, ensuring a longer shelf life for products. Given the concerns related to the costs of drying with fossil fuels and environmental pollution, the use of renewable energy is imperative. Burkina Faso benefits from more than 3,000 hours of sunshine per year, according to statistics from ANAM (the National Meteorological Agency of Burkina Faso). The objective of this study is the experimental analysis of a solar dryer with an unglazed parabolic trough collector. The work aims to evaluate its performance using new types of reflectors and absorbers, as well as to analyze the thermal performance of the collector and the dryer, and the drying kinetics of plantain and okra under real-world conditions. The studied products were washed and cut into homogeneous circular pieces and initially weighed, then distributed on the racks without overlapping. Irradiation and temperature data were recorded every five minutes. The measuring equipment included a data logger, a solarimeter, and an electronic balance. For 1000 g of banana, drying lasted 20 hours (over 2.5 days), with an average temperature of 50.9°C in the dryer. The final mass represented 32.8% of the initial mass. For 600 g of okra, drying took 8 hours, with an average temperature of 52.24°C. The final mass represented 9.66% of the initial mass. The average thermal efficiency of the collector was 68%. The overall efficiency of the dryer was evaluated at 20.24%. The average solar radiation recorded was 615 W/m². The drying kinetics for both products showed a decreasing phase, with a rapid reduction in moisture content at the beginning, followed by a gradual slowdown. The results are conclusive, highlighting that indirect solar dryers are a sustainable and cost-effective drying solution, offering better control over product quality.

Keywords: *dryer, solar irradiation, parabolic trough collector, thermal efficiency*

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1. Introduction

Post-harvest losses are a major cause of global food insecurity, impacting not only food availability but also the economies of farmers and populations dependent on these crops [1]. Food preservation is a major challenge to ensure a supply chain even in the absence of fresh produce and to promote food self-sufficiency. Drying is a viable alternative to reduce losses and ensure greater availability of products for human consumption. This technique, used for centuries, contributes to food preservation by reducing its moisture content [2].

The use of fossil fuels for drying highlights major concerns about costs and environmental pollution, highlighting the need for renewable energy such as solar power. Burkina Faso has an average sunshine of approximately 5.5 kWh/m²/day, making the sun a preferred energy source for the country. Solar drying is seen as an efficient and environmentally friendly technology, offering a low-cost way to dehydrate food products at low temperatures [3].

There are two types of solar dryers which are direct dryers and indirect solar dryers. Mixed and hybrid solar dryers are found in these two types. The literature shows that indirect solar dryers have better performance than direct solar dryers [4,5,6]. Many studies have been conducted on indirect solar dryer, taking into account works on dryer design, valorization of food products and medicinal plants. Specific research has concerned the drying of products such as mint, figs, mango, ginger, papaya and tomato. These researches have mainly demonstrated the applicability and optimization of indirect solar dryers for drying agro-food products [7-12].

Various studies have led to the construction of different models of indirect dryers. One example is the experiment by Dianda et al. [1], who designed an indirect solar dryer with forced convection incorporating an automatic temperature control system. They achieved a collector efficiency of 62% and product drying kinetics characterized by a solely decreasing phase. The work of Margarita Castillo Téllez et al. [13] focused on the design of an indirect dryer with solar collector coupling and thermal characterization by drying mint leaves. The experimental results showed that this model is an effective drying technology for drying mint.

Our work contributes to the improvement of indirect solar dryers. It involves improving the collector with small, unglazed parabolic trough reflectors (03). The collector is the main unit of the dryer; its improvement then leads to an improvement of the dryer. An experimental study on the drying of okra and plantain was conducted to determine the dryer's performance.

Our work contributes to the improvement of this dryer model through the use of new technologies.

2. Materials and Methods

Our device is an indirect solar dryer. It is composed of three (03) main parts: the thermal solar collector; the chamber; and the mobile support.

2.1. Materials

2.1.1. The Dryer

- The Solar Thermal Collector: This is the hot air production unit. It maintains an inclination of approximately 15°C from the horizontal and consists of the following elements:
  - Absorbers: These capture solar radiation and then convert it into heat. Our dryer uses three absorber tubes coated in a matte black color, increasing their absorption capacity ($\alpha = 0.97$).
  - Reflectors: Also three in number, with a parabolic trough geometry, they are covered with aluminum foil, concentrating the solar rays onto the absorbers.
  - Thermal Insulation: To reduce heat loss, 20 mm thick polystyrene covers the bottom and side surfaces of the collector. The collector is not glazed.
- The Drying Chamber: This is the enclosure where the products are placed for drying. It is made of lightweight 20 mm × 16 mm rectangular tubes and is insulated with polystyrene. The outer surfaces are made of black sheet metal and the inner surfaces are made of aluminum-zinc. The chamber is divided into three levels:
  - A lower section (0.3 m x 0.6 m x 0.6 m) for storing the dried products.
  - A central section (0.4 m x 0.6 m x 0.7 m) made of stainless steel racks, preventing corrosion and rust contamination of the products.
  - An upper section serving as an evacuation point for humid air using a thermosiphon effect.
- The Mobile Dryer Support : The dryer system relies on a pushcart that consists primarily of four metal supports: two 0.3 m high supports at the rear supporting the chamber-collector junction, and two 10 cm high supports at the front of the collector. The assembly is mounted on two wheels, allowing the device to be mobile.

Figure 1 shows the schematic of the solar dryer.

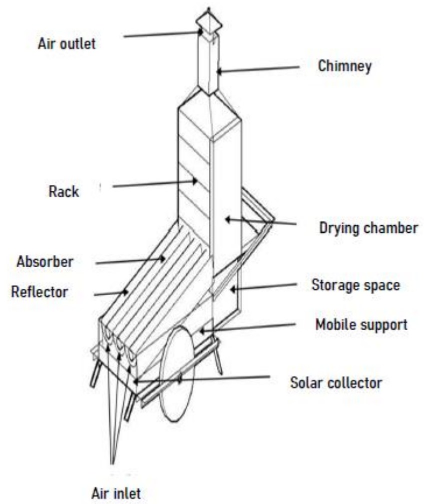


Figure 1. Design of the solar dryer

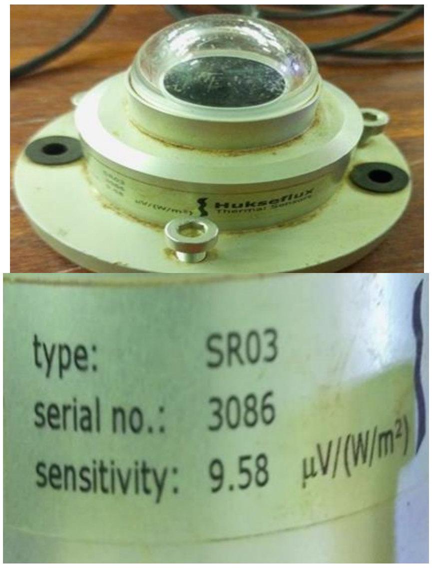
2.1.2. Devices Used

For the experimental study of the dryer, the following measuring devices were used :

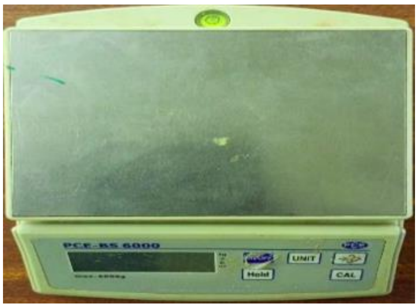
- A data logger : This is a MIDI LOGGER GL220 from GRAPHTEC Corporation, equipped with 10 thermocouple inputs. It measures temperatures ranging from -100°C to 1370°C with a margin of error of ±0.05%.
- A solarimeter : This device, used to measure solar radiation intensity, is a Hukseflux Thermal Sensor type SR03, with a sensitivity of 9.58 µV, equivalent to 1000 W/m² of solar irradiation.
- An electronic scale: This is a PCE-BS 6000 type scale with a maximum capacity of 6 kg. The scale is used to monitor the mass of the products during the drying process.

Figure 2 shows the various measuring devices.

a)



b)



c)

Figure 2. Measuring devices (a- Data logger, b- Solarimeter, c- Electronic Scale)

2.1.3. Drying Products

For this study, plantain and okra were selected.
Before drying,

Figure 3. Fresh banana and okra

2.2. Methods

2.2.1. Experimental Protocol

The products underwent rigorous processing, including washing to remove impurities, peeling to remove unusable parts, cutting into circular pieces of uniform thickness for uniform drying, draining, and initial weighing. The pieces were then evenly distributed on the racks without overlapping. During drying, hourly weighings were performed to determine the amount of water lost. Drying was considered complete when the mass of the products remained virtually unchanged between two successive measurements.

2.2.2. Theoretical Calculations

Dryer performance and the evolution of dried products are determined using the following relationships :

•**Initial moisture content (dry basis)** X_0 **:**

$$X_0 = \frac{m_0 - m_s}{m_s} \# \qquad (1)$$

m_0 is the initial mass of the product and m_0 is the dry mass.

•**Instantaneous moisture content** $X(t)$**:**

$$X(t) = \frac{m(t)(X_0 + 1) - m_0}{m_0} \# \qquad (2)$$

$m(t)$ is the mass of the product at the instant (t).

•**Thermal efficiency of the sensor** η_c **:**

$$\eta_c = F_R(\alpha\tau) - F_R(U_L)\frac{(T_s - T_e)}{I_t} \# \qquad (3)$$

Where

$F_R(\alpha\tau)$ is the optical efficiency, $F_R(U_L)$ is the overall heat loss coefficient, I_t is the incident solar irradiation, T_s is the air temperature at the sensor outlet et T_e is the air temperature at the sensor inlet.

•Dryer performance η :

$$\eta = \frac{M_e \times L_V}{N \times G \times S} \# \qquad (4)$$

Where

M_e is the mass of water extracted, L_V is the latent heat of vaporization of water (2,257. 10^6 J/kg15), N is the drying time, G is the average solar irradiation, and S is the surface of the sensor.

3. Results and Discussion

3.1. Empty Tests

No-load tests were carried out to characterize the operation of the vacuum dryer. Figure 4 illustrates the evolution of global solar irradiation.

A normal evolution of solar irradiation is observed. A rapid solar increase is observed, reaching its maximum of 889.7 W/m2 around 11 :30 a.m. and a gradual and regular decrease until the end of the day. A major characteristic of this curve is the abrupt drop in solar irradiation observed between 3 :00 p.m. and 3 :14 p.m., falling from nearly 450 W/m2 to approximately 200 W/m2, followed by a slight recovery around 400 W/m2. This fluctuation indicates the passage of clouds that temporarily obstruct the solar rays. The average solar radiation recorded this day (07/11/2024) is 615 W/m2.

The shape of this curve is similar to that found by Margarita Castillo Téllez et al [13].

All curves have the same appearance, namely a slight progressive increase and a slightly more rapid decrease. Their evolution (growth rate) is impacted by solar irradiation. The temperature in the absorber reaches a maximum of approximately 60°C, compared to approximately 55°C at the drying chamber inlet and 36°C at the inlet.

The figure demonstrates the efficiency of the solar collector in converting solar energy into thermal energy. The consistently highest temperature in the absorber confirms the role of the absorber as a heat transfer surface. This no-load test effectively characterizes the collector's potential to heat the air. Similar results have been found in several studies [14,15].

Figure 6 shows the evolution of the air temperature along the dryer racks.

The curves exhibited similar shapes throughout the test. The temperatures across the different racks were nearly identical. Maximum temperatures of approximately 53.5°C, 53.1°C, and 52.7°C were recorded on racks 1, 2, and 3, respectively. This is explained by the rapid passage of air without significant heat loss from one rack to another. Figure 7 provides critical information on the thermal performance and air distribution efficiency within the drying chamber. The near uniformity of temperature across the different racks is a very positive aspect for a dryer. It indicates efficient circulation and distribution of air and heat, which is important for uniform drying of produce. Similar results have been found by other authors such as Younas Khan et al [16].

Figure 7 presents the instantaneous collector efficiency as a function of time.

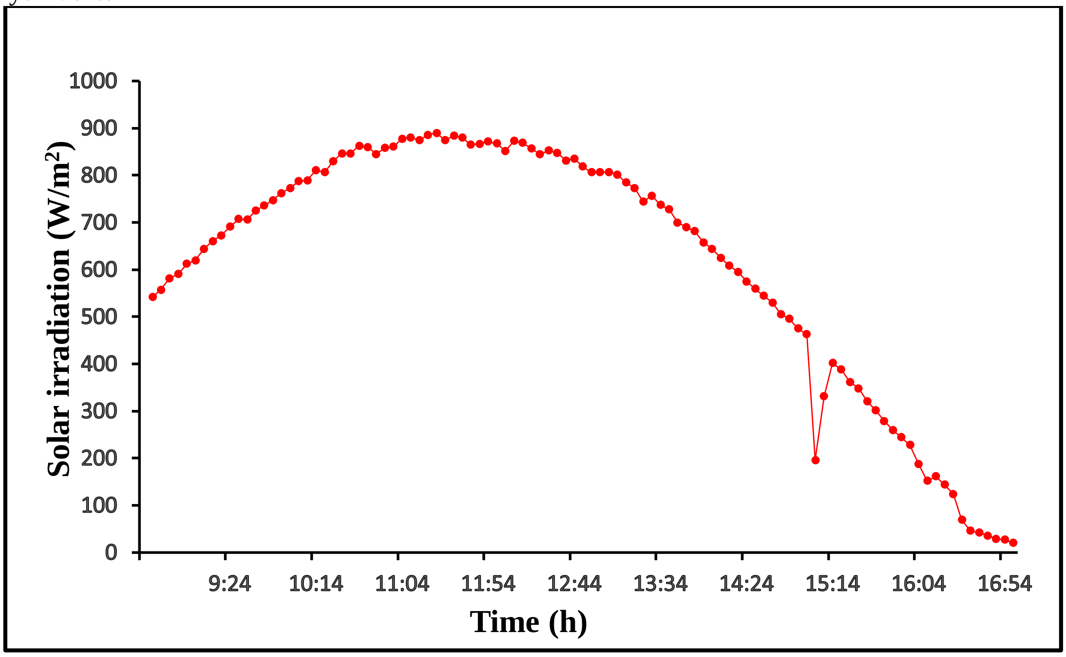


Figure 4. Solar irradiation variation curve for the day of 07/11/2024

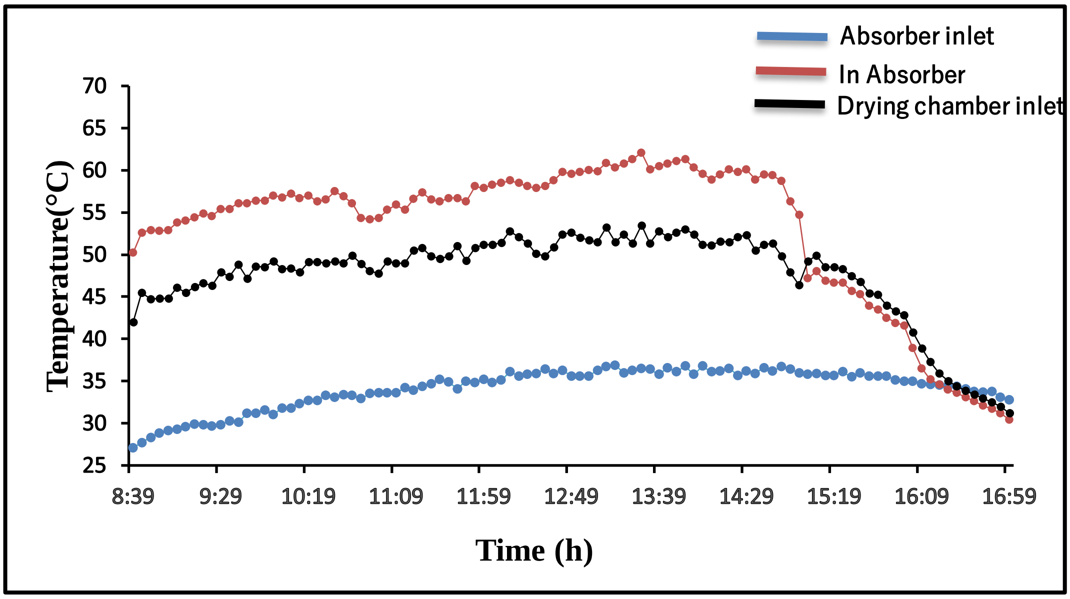


Figure 5. Temperature evolution in the sensor during the no-load test (07/11/24)

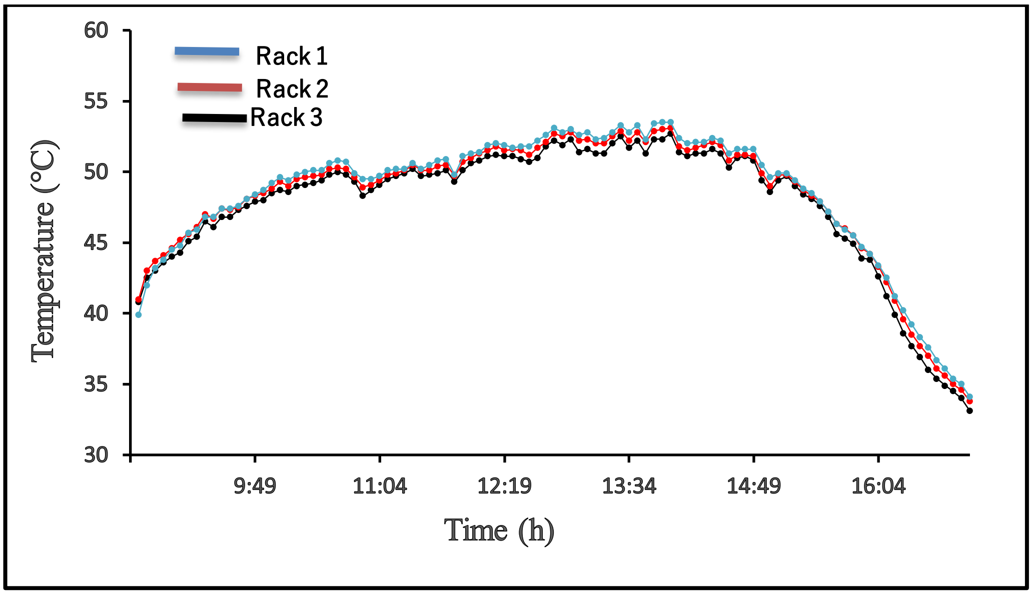


Figure 6. Temperature evolution in the dryer during the no-load test (07/11/24)

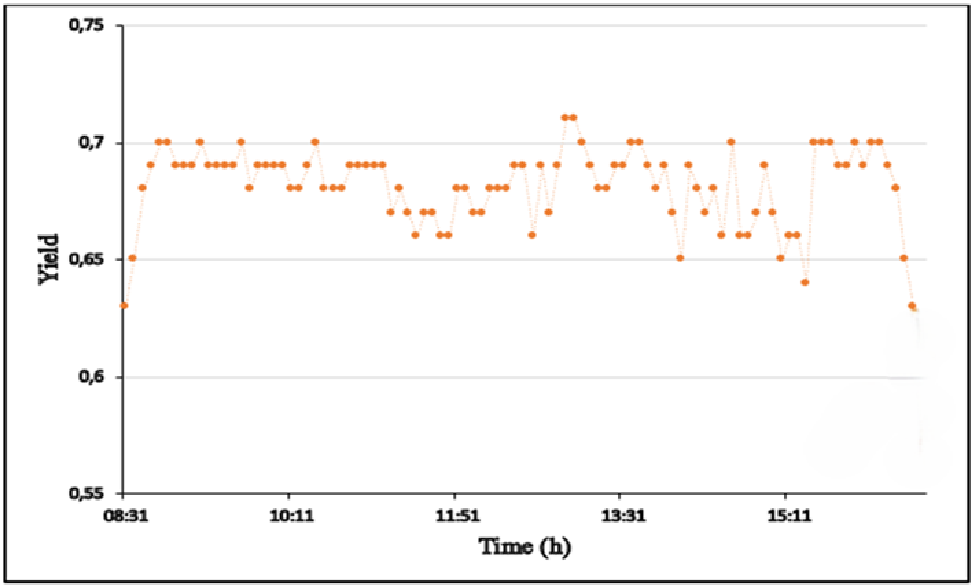


Figure 7. Representation of the solar collector efficiency during no-load experiments

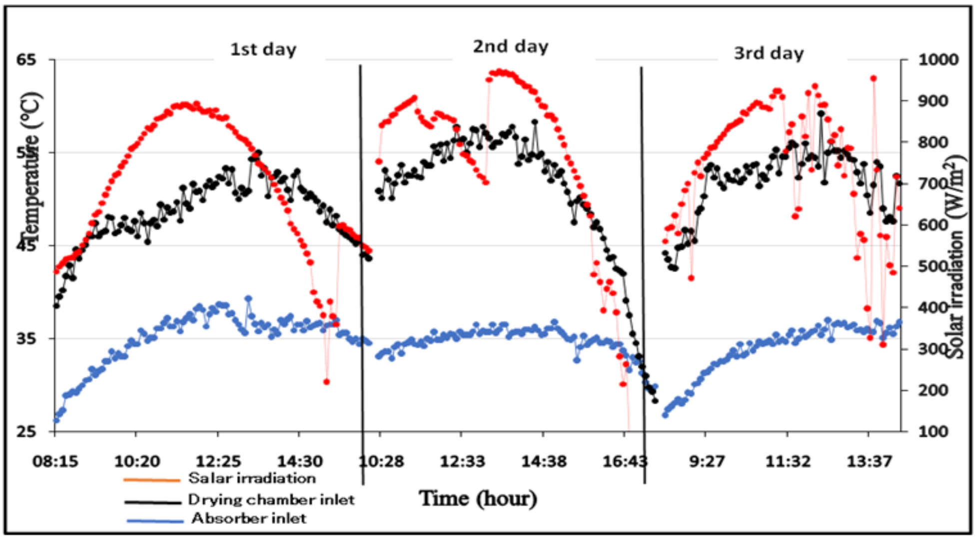


Figure 8. Evolution of solar irradiation, air temperature at the absorber inlet and at the storage chamber inlet during plantain drying (11-13/11/2024)

The efficiency varies between 0.65 and 0.70 over most of the test day. A slight drop in efficiency is observed between around 3:16 PM and 3:26 PM. An efficiency between 65% and 70% is considered very good for an air-source solar thermal collector, especially under no-load test conditions where the collector does not provide useful work for water evaporation. This indicates an efficient collector, maximizing the concentration and conversion of solar radiation. Fluctuations in efficiency are due to small variations in solar flux, ambient temperature, or airflow rates that were not perfectly constant. The drop in efficiency observed after 4:00 PM is consistent with the sharp decrease in solar flux. At low irradiation, heat losses become relatively larger compared to the captured energy, causing the efficiency to drop. This efficiency is identical to that found by Hajar Essalhi [10].

3.2. Load Testing

The feedstocks used for drying were okra and plantain. Figure 8 shows the changes in solar irradiation and air temperatures at the inlet and outlet of the absorber for three consecutive days of plantain drying.

Solar irradiation is often disrupted by cloud cover. The maximum values recorded over these three days were approximately 890 W/m², 970 W/m², and 930 W/m², respectively. The temperatures at the dryer inlet and the chamber outlet followed the general radiation trend, reaching maximums between 55-60°C and 35-40°C, respectively. The relatively high air temperature at the collector outlet, corresponding to the chamber inlet, demonstrates good collector performance, providing adequate thermal energy for the drying process. The temperature difference between the collector inlet and outlet is significant (approximately 25°C at the maximums).

Figure 9 shows the temperature evolution at racks 1, 2, and 3 during the drying of plantain bananas.

The air temperature curves on the racks have the same appearance. They gradually increase over the hours and days. On the first day, temperatures reach a peak of approximately 52°C. On the second and third days, the peaks are slightly higher, approximately 57°C. As in the no-load test, a slight stratification of temperatures is observed between the racks. Rack 1, closer to the hot air inlet, is warmer than rack 2, which is also warmer than rack 3. The increase in temperatures on the racks over the days is a typical drying phenomenon: as the product loses moisture, there is less water to evaporate. The slight stratification of temperatures between the racks is expected in the load test, as the air cools down as it passes through the product layers and absorbs moisture. However, this stratification remains limited, which confirms a good design of the air circulation, ensuring relatively uniform drying. Other authors find similar results [17-19]

Figure 10 shows the changes in solar irradiation and air temperature at the inlet and outlet of the absorber during okra drying.

The solar irradiation profile is typical, with a peak around 700 W/m². The air temperature changes at the inlet and outlet of the absorber are very similar to those observed during banana drying, reaching peaks of approximately 38°C and 59°C, respectively. These very similar trends confirm the collector's ability to provide hot air even with different loads.

Figure 11 illustrates the temperature changes on the different racks during okra drying.

The temperatures on the racks follow a similar pattern, increasing to a peak of about 55°C. Air temperatures are higher from rack 1 to rack 2 during the drying period. The temperature stratification between the racks is more pronounced for okra than for plantain. These findings are similar to those of S. Boughali et al [15]. Figures 12 and 13 illustrate the variation in moisture contents during drying of banana and okra respectively.

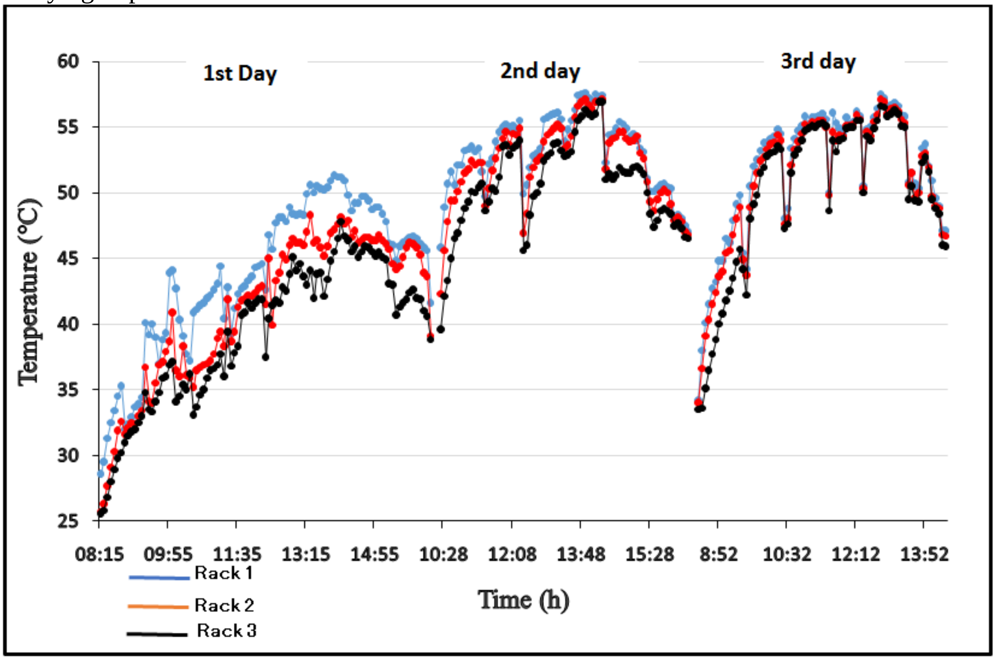


Figure 9. Evolution of air temperature on the racks during plantain drying (11-13/11/2024)

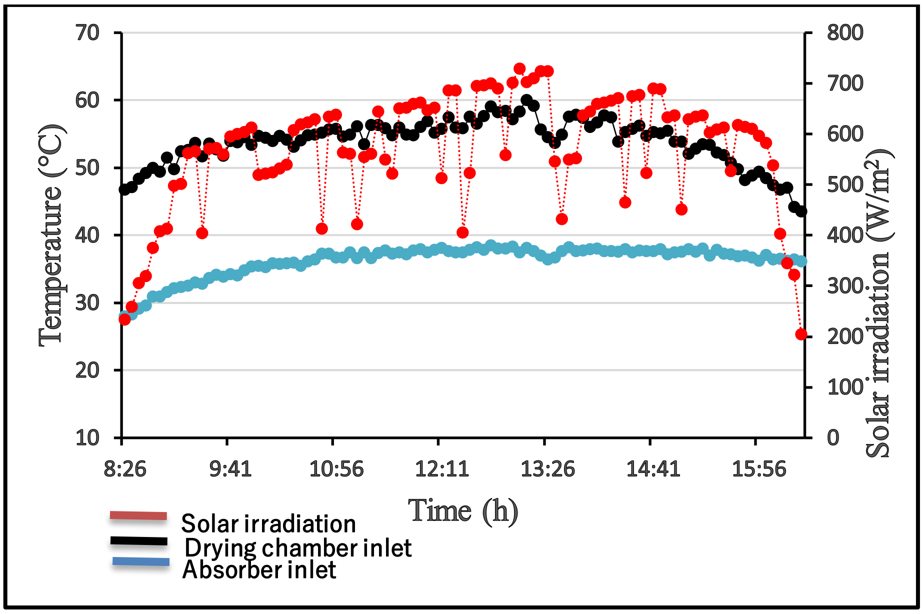


Figure 10. Evolution of solar radiation, air temperature at the inlet and outlet of the collector as a function of time during okra drying (11/14/2024)

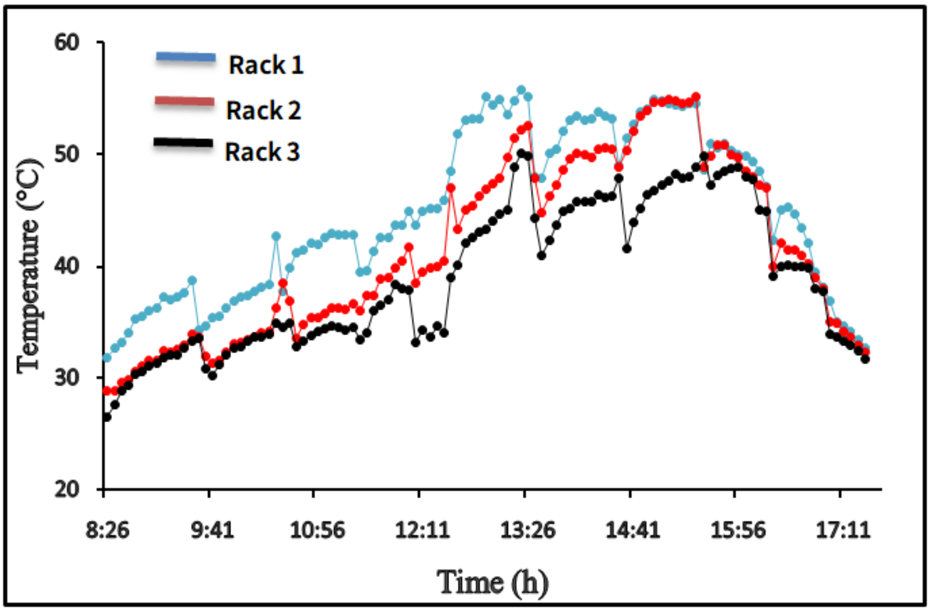


Figure 11. Temperature evolution on the racks during okra drying (11/14/2024)

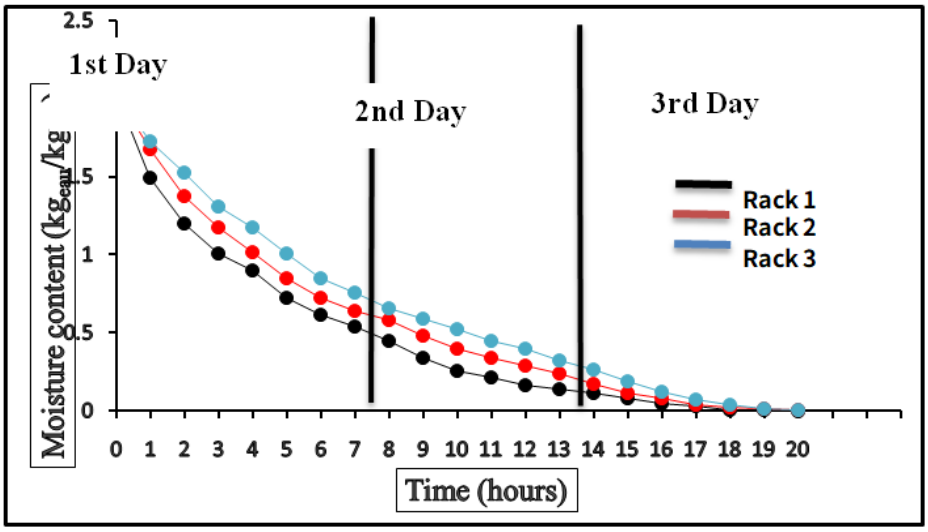


Figure 12. Variation in moisture content of plantain banana during drying on November 11-13, 2024

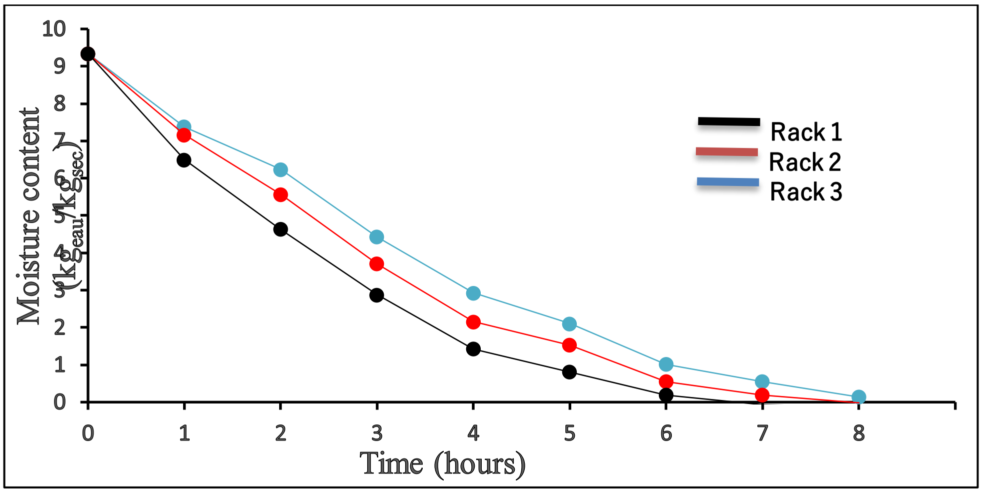


Figure 13. Variation in moisture content of okra during drying on November 14, 2024

For all racks, whether for drying okra or banana, the moisture content decreased continuously over the drying time, indicating an effective drying process. Rack 1 dried the fastest, followed by Rack 2, and Rack 3 came last. This ranking is mainly due to the arrangement of the racks relative to the inlet of the heated air from the absorber. Indeed, the hot air entering through the first rack is loaded with calories, allowing it to evaporate more water from the produce on that rack. As the air moves along the racks, it loses its ability to evaporate water from the produce. These results are consistent with those in the literature [1,11,20].

•Dryer efficiency:

The overall efficiency of the dryer was evaluated using equation 4 and is 20.24%. This yield is better than that obtained by Hajar Essalhi [10] who found a yield of 11.11%.

Summary of dryer performance

Table 1. Summary of dryer performance

Parameters	Plantain	Okra
Initial weight	1000 g	600 g
Final weight after drying	328 g	58 g
Final remaining weight	32,8% of initial weight	9,66% of initial weight
Drying time	20 hours (over 2,5 days)	8 hours
Average collector thermal efficiency	68%	68%
Overall dryer efficiency	20,24%	20,24%

This observation demonstrates the effectiveness of our dryer

4. Conclusion

This work evaluated the performance of an indirect solar dryer with a parabolic trough collector without glazing. The results demonstrate the efficiency of this system for the processing of agri-food products, with an average thermal efficiency of 68% for the collector and an overall efficiency of 20.24% for the dryer. The drying process, defined by heat transfers from the air to the products and the expulsion of moisture to the outside, favored the obtaining of satisfactory final product masses (32.8% of the initial mass in 20 hours when drying plantain bananas and 9.66% of the initial mass in 8 hours when drying okra). Improving the collector improves the quality of the dryer. However, there are prospects for improvement. This involves including a thermal storage system and a temperature control device in the dryer.

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